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Information Processing and Proactive Interference in Children With and Without Specific Language Impairment

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Abstract

Purpose—Increasing evidence suggests that children with specific language impairment (SLI) have a deficit in inhibition control, but research isolating specific abilities is scarce. The goal of this study was to examine whether children with SLI differ from their peers in resistance to proactive interference under different conditions.

Method—An information processing battery with manipulations in interference was administered to 66 children (SLI, age-matched peers, and language-matched controls). In Experiment 1, previously relevant targets were used as distractors to create conflict. Experiment 2 used item repetitions to examine how practice strengthens word representations and how the strength of a response impacts performance on the following item.

Results—Children with SLI performed similarly to their peers in the baseline condition but were more susceptible to proactive interference than the controls in both experimental conditions. Children with SLI demonstrated difficulty suppressing irrelevant information, made significantly more interference errors than their peers, and showed a slower rate of implicit learning.

Conclusion—Children with SLI show weaker resistance to proactive interference than their peers, and this deficit impacts their information processing abilities. The coordination of activation and inhibition is less efficient in these children, but future research is needed to further examine the interaction between these two processes.

Keywords

proactive interference; inhibition; executive functions; perseveration; SLI

Adaptive and flexible behavior is essential in any learning situation. To perform well on various cognitive tasks, children need to mobilize complex cognitive processes, such as executive functions including working memory, inhibition, and attention control. These executive functions play an important role in different learning situations, including language acquisition and processing (Mazuka, Jincho, & Oishi, 2009). Executive functions develop with age, and children with neurodevelopmental disorders, such as specific

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language impairment (SLI), show limitations in these skills (Im-Bolter, Johnson, & Pascual-Leone, 2006). The present study focuses on inhibition because of the critical role it plays in learning, problem solving, and efficient working memory function (Posner & Rothbart, 2000).

Interference Control

The literature is inconsistent regarding the definition and nature of interference control (e.g., Miyake et al., 2000; Wilson & Kipp, 1998). We based our study on the Friedman and Miyake (2004) model, in which interference control is one form of inhibition. The authors differentiate among three inhibition functions: (a) inhibition of a prepotent response, (b) resistance to distractor interference, and (c) resistance to proactive interference. Inhibition of a response refers to the blocking of an automatic behavior in response to a stimulus (e.g., stopping ongoing activity when a red light turns on). Distractor interference control is about resisting external stimuli (e.g., choosing the appropriate picture from a pool that consists of targets and competitor or distractor items), whereas proactive interference control is about resisting internal sources (memory traces) that may hinder efficient information processing (e.g., suppressing irrelevant information from previous tasks). Our present study focused on proactive interference only.

Different components of inhibition show different developmental trajectories. Response inhibition develops earlier than interference control (Mazuka et al., 2009; Ridderinkhof, Band, & Logan, 1999). The neural correlates associated with these components differ as well. Response inhibition has been found to be associated with the fronto-striatal network, whereas resistance to both distractor and proactive interference has been found to be related to the parietal and medial–frontal regions (Sebastian et al., 2012). Although these inhibition functions are distinct, they are closely related to each other and to working memory. There is an ongoing debate in the literature about the reasons for individual differences in working memory capacity. Numerous working memory models suggest that resistance to proactive interference is a key component (e.g., Hasher, Lustig, & Zacks, 2007). Proponents of the interference control view assume that more effective resistance to interference is related to larger working memory capacity because relevant and irrelevant representations compete for the same limited working memory capacity. Thus, people who are more efficient in resisting interference from irrelevant information (external or internal) have more free working memory capacity. Recent research has suggested that interference control plays a major role in poor working memory performance in different clinical populations, such as children with autism (Adams & Jarrold, 2012) and individuals with reading disabilities (Chiappe, Siegel, & Hasher, 2000). These findings motivated the current study, which examined whether problems in proactive interference contribute to the working memory deficit in children with SLI.

A common way of testing proactive interference is by using task switching paradigms that examine how previously relevant but currently irrelevant information may cause interference during subsequent problem solving (Unsworth, 2010). A well-known phenomenon in the task switching literature is the switch cost effect. Switching from one task to another causes decrements in performance, such as increased reaction time (RT; e.g., Rogers & Monsell, 1995). One explanation for this effect is that switch costs reflect the extra time needed to reconfigure the cognitive system for a new task (e.g., Meiran, 1996). An alternative interpretation is that the longer RT is the result of a carryover effect (e.g., Hsieh & Liu, 2005). In both cases, the prolonged period of time reflects interference between previous and current tasks or items. Overall, the interference literature suggests that task similarity, short processing time, and simultaneous working memory demands may all increase interference among different stimuli (Best & Miller, 2010). We examine some of these factors—task similarity and age—in Experiment 1 of the current study. An alternative view to the interference control models is that individuals perform poorly in task switching paradigms when their previous working memory representations are stronger than their current representations. Morton and Munakata (2002) suggested that proactive interference occurs when the working memory representation of the previously relevant item is stronger than that of the currently relevant item. Thus, the critical function, according to this view, is not the suppression of previously relevant information but the strengthening of the currently relevant material. This hypothesis was examined in Experiment 2 of the current study.

Inhibition Control in Children With SLI

There are only a few studies that have examined specific executive functions, such as inhibition control (Spaulding, 2010) or sustained attention (e.g., Finneran, Francis, & Leonard, 2009), with well-designed experiments in children with SLI. Most studies have used complex tasks that measured various executive functions simultaneously and thus were unable to identify a specific locus of deficit. Although there is evidence in the literature that inhibition control plays an important role in language processing (e.g., Snyder et al., 2010), only a few studies have focused directly on inhibition control in children with SLI. Prepotent response inhibition has been examined in preschool- and school-age children with SLI, with inconsistent results. Preschool-age children with SLI showed more errors in response inhibition than their peers with typical language development (TLD) in a go/no-go task, in which children are required to withhold their response (Spaulding, 2010). In contrast, school-age children with SLI performed similarly to age-matched peers and faster than language-matched (younger) participants in a stop–signal task requiring response inhibition (Marton, Campanelli, Scheuer, Yoon, & Eichorn, 2012). Similarly, there was no group difference at the behavioral level between school-age children with SLI and TLD in a go/no-go task (Tropper, 2009) and in intentional visual inhibition (Dodwell & Bavin, 2008). Children with good and poor reading comprehension did not differ in blocking an automatic response in the animal Stroop and Hayling tasks either (Borella, Carretti, & Pellegrina; 2010). These findings suggest that children with SLI initially show slower development of response inhibition than do their TLD peers but that this group difference disappears by school age.

In contrast to response inhibition, deficits in resisting distractor interference have been reported across a wide age range in children with SLI. Preschool-age children with SLI had difficulty suppressing irrelevant information and resisting distractor interference, regardless of modality (Spaulding, 2010). These children performed more poorly than their TLD peers with visual, nonlinguistic auditory, and linguistic distractors. School-age children with SLI demonstrated the same difficulties on a visual matching-to-sample task (Marton et al., 2012), in which they showed increased reaction times compared with both age-matched and language-matched peers when asked to find the matching pair of a visual pattern among similar stimuli. The findings indicated poor resistance to distractor items. Similarly, school-age children with SLI showed increased phonological interference compared with their TLD peers when auditory distractors were presented during a picture-naming task (Seiger-Gardner & Brooks, 2008). A comparison of children with good versus poor comprehension on tasks measuring proactive interference likewise found more interference errors in poor comprehenders, who showed difficulties with controlling irrelevant information at retrieval and suppressing activated items (Borella et al., 2010).

The results from a number of working memory studies also suggest that poor interference control is a possible explanation for the weak working memory performance in children with SLI. Several studies have showed that these children fail to exhibit primacy and recency effects in linguistic span tasks (Ellis Weismer, Evans, & Hesketh, 1999; Marton, Kelmenson, Pinkhasova, 2007; Marton & Schwartz, 2003; Marton, Schwartz, Farkas, & Katsnelson, 2006). It has been suggested that diminished primacy and recency effects reflect poor resistance to distractor and proactive interference. This interpretation of results is supported by the finding that children with SLI had particular difficulty inhibiting lexical items that were the focus of previous searches. Furthermore, a deficit in using contextual information in children with SLI was evidenced in a lexical ambiguity resolution task (Norbury, 2005). Children with SLI showed deficient contextual facilitation, in addition to poor suppression of irrelevant information. They also showed deficits in processing both facilitative and ambiguous contextual information. Poor resistance to both distractor and proactive interference was evidenced by school-age children with SLI on a listening span task (Marton et al., 2007), in which children with SLI had difficulty suppressing irrelevant information and expelling unnecessary material from working memory. The error analysis data showed that children's responses were often perseverative in nature. They repeated previously correct items even when the conditions changed. Their answers also reflected contextual distraction. Instead of repeating the sentence-final items, they repeated words from the questions that targeted the processing of sentence content. Although these findings indicated problems in interference control in children with SLI, the main tasks in that study were designed to measure working memory capacity and not interference control. In contrast, the present study was specifically designed to directly examine resistance to proactive interference in children with SLI.

Taken together, the data from different studies across modalities suggest that the inhibition problems of children with SLI are not limited to specific modalities and that different types of inhibition are not uniformly affected. Although response inhibition shows a delay in preschool-age children, it is age appropriate in school-age children. In contrast, resistance to distractor interference shows a deficit across different age groups with SLI. This weakness is evidenced in visual and auditory modalities and in both verbal and nonverbal domains. On the basis of these findings, the current study focused on resistance to proactive interference. Our goal was to answer the following research questions: (a) Do children across groups (SLI, age-matched, and language-matched controls) show similar degrees of interference in a conflict condition where previous target items become distractors (Experiment 1)? (b) Does the strength of a given item's representation impact children's responses to the following items, as suggested by the Morton and Munakata (2002) model? Specifically, do children's responses to items that follow a highly practiced item show an increase in reaction time, reflecting greater proactive interference (Experiment 2)?

Experiment 1

In Experiment 1, we tested proactive interference by using a conflict paradigm, in which previous target items served as distractors in subsequent tasks. We examined sensitivity to internal stimuli—specifically, interference from previously relevant material—and compared performance on interference trials with performance on baseline items that did not involve interference. If items from previous trials are not deleted efficiently from working memory, then recalling goal-relevant information becomes more difficult because of response competition. This can be reflected in lower response accuracy and increased RT (Robert, Borella, Fagot, Lecerf, & de Ribaupierre, 2009) as well as more frequent perseverative errors. Previous studies from our research group have showed a greater number of perseverative errors in children with SLI compared with their peers across various verbal and nonverbal tasks, including working memory (Marton, 2009; Marton et al., 2007). One possible explanation for these errors could be poor resistance to proactive interference. Accordingly, we tested the following hypotheses:

1. There will be no group difference in accuracy (ACC) for the baseline condition (Hypothesis 1a). The RT data will show an age effect: Language-matched children with typical language development (TLD-L) will perform more slowly than the age-matched children with typical language development (TLD-A) and SLI groups (Hypothesis 1b). Children with SLI will not show a general slowness effect; therefore, their RT data in the baseline condition will be comparable to those of the TLD-A group (Hypothesis 1c).

2. Children with SLI will show a greater performance decrement in the interference condition compared with the baseline condition than will the control groups. Thus, the interference condition will have a larger negative effect on both ACC (Hypothesis 2a) and RT (Hypothesis 2b) in children with SLI than in children with TLD. The interference condition will have similar effects on the children in the TLD-L and TLD-A groups: They will all show increased RT compared with the baseline measures (Hypothesis 2c), but there will be no difference in ACC across conditions because of the simplicity of the task (Hypothesis 2d).

Method

Participants—Three groups were formed on the basis of children's age and language status: 22 children with SLI, 22 age-matched children (±3 months based on group means) with typical language development (TLD-A); and 22 language-matched controls (TLD-L). The age range (in months) for the SLI, TLD-A, and TLD-L groups was 120–170, 100–179, and 96–162, respectively. All children spoke English as their primary language, had normal hearing based on a hearing screening performed at 20 dB between 250 and 8000 Hz, and had no reported developmental disorder other than SLI. Parental permission and verbal assent were obtained from all participants. All children scored within the average range (standard score > 85) on the Test of Nonverbal Intelligence—Third Edition (TONI–3; Brown, Sherbenou, & Johnsen, 1997; see Table 1 for further details related to participant characteristics).

We administered several standardized language measures to all participants to verify language status and to determine appropriate group assignment. These included Core Language subtests on the Clinical Evaluation of Language Fundamentals, Fourth Edition (CELF–4; Semel, Wiig, & Secord, 2003); the Expressive One-Word Picture Vocabulary Test (EOWPVT; Brownell, 2000); and the Test for Reception of Grammar, Second Edition (Bishop & Garsell, 2003). Children in both control groups (TLD-A and TLD-L) achieved scores within the average range (standard score > 85) across all language measures. Children with SLI were all previously diagnosed by a certified speech-language pathologist, had received several years of speech-language therapy, were continuing to receive treatment at the time of the study, and scored at least 1.25 standard deviations below the mean of the age-matched children's language scores on the CELF and on one or two additional standardized language measures. All children with SLI also had a documented standardized score at least 1.25 standard deviations below the mean on a complex language measure administered on an earlier date, typically at the time of diagnosis.

The TLD-L group was matched with the SLI group on the basis of performance on the Recalling Sentences sub-test of the CELF–4 (±3 raw score units). Preliminary data collected during the early phase of the study demonstrated that this subtest was most sensitive in identifying children with SLI and differentiating groups (see Table 1). All participants also completed a verbal working memory task to ensure that the TLD groups showed age-appropriate working memory performance. On the basis of previous findings, children with SLI were expected to perform more poorly than their peers. Participants were required to listen to increasingly long lists of items (2–6 items) belonging to a particular category (e.g., animals), then reorder and repeat the items on the basis of a given criterion (e.g., increasing size). The most common errors were deletions, substitutions, and perseverations. Perseverative responses were defined as items presented on an earlier list but not included in the current trial. Children with SLI performed more poorly on the working memory task than did the two other groups. Mean number of perseverative errors for each group is presented in Table 1. Results of two-sample Student's *t* tests confirmed that children with SLI made significantly more perseverative errors than did their age-matched peers, $t(42) = 2.95$, $p = .005$; as well as language-matched children, $t(42) = 2.61$, $p = .012$. This is consistent with previous findings in the literature.

Procedures and stimuli—The total time of participation was approximately 5 hr, with tasks completed in 2–3 sessions. Screening procedures and experimental tasks were varied throughout each session to minimize fatigue. All experimental tasks were administered via a tablet computer using colored, round 2 1/2-in. response buttons (two black and one red). Buttons were positioned 2–3 in. away from the edge of the table in front of each participant and arranged so that the red button was in between the two black ones. Children were tested in the laboratory or in quiet rooms located in participating private practices or schools.

The experimental task consisted of an original information processing battery adapted from the selective reaching task described by Klimkeit and colleagues (Klimkeit, Mattingley, Sheppard, Farrow, & Bradshaw, 2004). Our complete battery consisted of 10 tasks that were similarly structured but that included specific manipulations to examine different aspects of inhibition control. Task order was randomized to control for practice or other task order effects. Experiments 1 and 2 focused on a subset of tasks from the full battery, which was administered as part of a larger study on inhibition control in school-age children with SLI. Tasks in both experiments involved category judgments for familiar high-frequency words and consisted of 84 items each. We used the data from Hall, Nagy, and Linn (1984) for frequency ratings. All tasks included words that children typically acquire during the preschool years, so the linguistic component of the task was very simple for our target populations. The task was created to be simple because we were not interested in measuring children's categorization abilities. A category name (e.g., "Family") appeared on the screen followed within 1–2 s by either a target word that belonged to the category (e.g., "Mother") or a distractor item that did not ("Ball"; see Figure 1). All words were presented visually and read silently by participants. Participants were instructed to press and hold the red response button, then release the red button as soon as the category name appeared. For target words, participants were required to press the black button corresponding to the side on which the target word appeared. For distractor words, participants were required to withhold responses on the black buttons and press the red button in the center. Pressing the red button for nontarget responses was necessary to differentiate withheld responses from failure to respond (in which no buttons were pressed). Participants were instructed to respond as quickly and as accurately as possible. Failure to respond within 5 s triggered automatic presentation of the subsequent trial.

Experiment 1 included specific manipulations designed to increase proactive interference by using previous target words as distractors. Out of the 168 items in the task, a distractor item was presented on 48 items. Half of these distractor items (24) consisted of words that belonged to the preceding category and had been presented as targets. Performance on items that used previous target words as distractors in current trials was used to measure resistance to proactive interference and represented the interference condition. The remaining 24 distractors did not belong to any previously presented category and served as the baseline condition. The baseline condition included new distractor items only. Accuracy and RT data for all button-press responses were automatically collected by the computer during task administration.

Results

ACC data—Linear mixed-effect models were used to test the hypotheses of this study. Model building followed a bottom-up theory-guided approach, starting with Level 1 predictors. A model comparison framework was used to contrast alternative models that were progressively more complex. The likelihood ratio (LR) test and the Akaike information criterion (AIC) were used to compare the fit of competing models. Tables of descriptive statistics and results of linear mixed-effect model comparison for present and subsequent analyses are available online as supplementary materials. We started building the Level 1 model by adding the interference condition as a dummy-coded factor (baseline condition as a reference level) to the null model, which improved the model fit, $\chi^2(1) = 32.96$, $p < .001$. Building the subject-level model, we included nonverbal IQ (TONI–3) and vocabulary (raw scores from the EOWPVT) as covariates and tested whether these variables moderated the relationship between the interference factor and performance accuracy. Only the Vocabulary × Interference interaction improved the model fit, $\chi^2(1) = 3.94$, $p = .047$; therefore, the Nonverbal IQ × Interference interaction was excluded in subsequent models, $\chi^2(1) = 1.14$, $p = .285$.

The group factors, with TLD-A as the reference level, did not show a significant effect on the reference task and did not improve the model fit, $\chi^2(2) = 1.97$, $p = .373$; indicating that the three groups did not differ in baseline performance accuracy, thus supporting Hypothesis 1a. Furthermore, similar baseline performance across groups shows that none of the children had difficulty reading the words or performing the task at a basic level. Trials in which there was a failure to respond within the 5-s window were rare. They constituted only 3%–4% of all errors in each group. This proportion was similar across groups and tasks, suggesting that children paid attention to the tasks and followed the instructions. Those few cases where a child failed to respond were not included in the analyses.

Hypothesis 2a predicted that children with SLI would demonstrate a greater interference effect than both TLD groups. We found that SLI, $\chi^2(1) = 6.64$, $p = .01$, but not TLD-L, $\chi^2(1) = 0.04$, $p = .842$, interacted with the Level 1 factor Interference, supporting Hypothesis 2a (disproportional interference in children with SLI compared with TLD participants).

On the basis of both the AIC and LR test, we selected the model shown in Table 2 as best fitting model. This model shows that the interference condition had an overall significant negative effect on performance accuracy in all groups: This does not support our prediction (Hypothesis 2d) of no difference in ACC across conditions for the TLD groups. This model also shows that vocabulary had a significant positive effect on performance accuracy in the baseline condition. Nonverbal IQ did not have a significant effect but was kept in the model as a covariate. Estimated accuracy for all children in the baseline condition, for average nonverbal IQ and vocabulary, was .84. The Interference × Vocabulary interaction further indicates that the interference effect was greater in children with high vocabulary scores than in children with low vocabulary scores.

Similarly, the Interference × SLI interaction indicates a greater interference effect in children with SLI compared with controls (Hypothesis 2a), with an estimated interference effect of .048 (5.6% ACC drop) in TLD children and .1 interference effect (11.6% ACC drop) in children with SLI. Language status thus implies an interference effect in children with SLI that is 108.3% greater than that estimated in controls.

RT data—Next, we tested hypotheses related to RT. All RT analyses were based on correct responses only. The Level 1 factor Interference was added to the null model, resulting in a better fit to the data, $\chi^2(1) = 5.19$, $p = .023$. Nonverbal IQ and vocabulary (raw scores) were entered as subject-level covariates, along with their cross-level interactions with the Interference factor. Effects of nonverbal IQ and vocabulary on the baseline condition were kept, regardless of significance level, in order to control for these covariates. However, only the Interference × Vocabulary interaction was retained, $\chi^2(1) = 5.22$, $p = .022$; as the Interference × Nonverbal IQ interaction did not yield a better fit to the data, $\chi^2(1) = 1.79$, $p = .18$.

In examining group effects, we found that the model that included TLD-L, $\chi^2(1) = 9.94$, $p = .002$, but not SLI, $\chi^2(1) = 1.31$, $p = .252$, showed a significantly better fit to the data. This finding supports Hypothesis 1b, which predicted an age effect on RT in the baseline condition, with younger children performing more slowly than the older groups; and Hypothesis 1c, which predicted no language status effect. Thus, the children with SLI performed similarly to their age-matched peers in the baseline condition.

Cross-level interactions, including Interference × SLI, $\chi^2(1) = 0.04$, $p = .84$, and Interference × TLD-L, $\chi^2(1) = 1.13$, $p = .288$, did not yield a better fit. The latter finding indicates that the negative interference effect on RT was significant but comparable across groups, supporting Hypothesis 2c (all groups show an interference effect in RT) but not Hypothesis 2b, which predicted disproportional interference in SLI.

The final model best fitting our data is shown in Table 2. On the basis of this model, the interference condition had a significant effect on RT, with an estimated increase of 46 ms over the baseline performance of 1,344 ms. This increase in RT corresponds to an interference effect of 3.4% in SLI and TLD-A children and a 3% interference effect in TLD-L children, assuming average nonverbal IQ and vocabulary. TLD-L children were significantly slower than older children (SLI and TLD-A), with an estimated difference of 215 ms between age groups.

Discussion

The ACC results of Experiment 1 show that children with SLI performed similarly to their typically developing peers in the baseline condition, where all target and distractor items were new. Only the RT data showed a group effect, with TLD-L children performing more slowly than the two older groups (TLD-A, SLI; see further details below). Vocabulary size showed a positive effect on performance accuracy in the baseline condition regardless of language status. Children with larger vocabularies performed more accurately than did children with smaller vocabularies. Activation of a category name may result in activation of related items (see semantic network models on word associations; e.g., Steyvers & Tenenbaum, 2005). Children with larger vocabularies may have activated more items related to the category name than did children with smaller vocabularies. Consequently, the higher activation levels of these words may have promoted selection of correct items.

Our hypothesis regarding the interference condition was that children with SLI would show a greater performance decrement between the baseline and the interference conditions than the controls because children with SLI have a weakness in differentiating between task-relevant items and irrelevant ones and in suppressing irrelevant information (Marton et al., 2007; Norbury, 2005). Accuracy measures for the interference condition compared with the baseline decreased for all groups, but this negative effect was larger for the children with SLI than for the two control groups. This finding suggests that children with SLI show weaker resistance to proactive interference than do their peers.

The decrease in performance ACC across conditions in the control groups was unexpected. We proposed an interference effect in RT but not in ACC because the task was easy for the typically developing children. This outcome might reflect that both resistance to proactive interference and working memory are still developing in school-age children (Mazuka et al., 2009). A conflict paradigm with competing items is highly demanding on inhibition control, so even children with relatively good inhibition skills may show an increase in interference errors. The larger negative effect of the interference condition on performance ACC in children with SLI suggests that these children had even more difficulty with inhibition control. According to the failure-to-inhibit hypothesis (Fischer-Baum & Rapp, 2012), inhibitory processes are needed to lower the activation levels of previous items prior to the onset of the next trial. Children with TLD were more efficient than the children with SLI in removing irrelevant information from their working memory when the target items became distractors. Thus, children with TLD used their inhibitory functions more effectively.

A further hypothesis for Experiment 1 was that all groups showed an interference effect in RT. In contrast to the ACC measures, where children with SLI showed a larger performance decrement between conditions than control groups, all participants were equally affected by the interference condition in their RT responses. Everyone showed increased RT, and this change was comparable across groups. As in the baseline measures, the interference data showed an age effect, with younger children (TLD-L) performing more slowly than older children (SLI, TLD-A). The developmental literature is inconsistent regarding the age effect. Some researchers found an age effect in RT across different executive functions, including response inhibition (Best & Miller, 2010). Kail (2002) also reported an age effect in resistance to proactive interference on the basis of results of a meta-analysis, but this age-related performance decrement was shown only using aggregated data. The individual studies did not report such an effect. The results of structural equation modeling showed no direct link between age and pro-active interference in the final model. The developmental changes were mediated by children's speed of processing (Kail, 2002). More research is needed to clarify the conditions and task types that show an age effect in children's RT measures.

The Interference × Vocabulary interaction suggested that in tasks with minimal interference, such as our baseline, children with larger vocabularies show an advantage. This benefit disappears, however, with an increase in interference level. Children with larger vocabularies showed a larger interference effect than did children with smaller vocabularies. There may be several reasons for this outcome. Larger vocabulary may be associated with better working memory skills; most children with larger vocabularies were older than children with smaller vocabularies. Thus, the outcome may indicate an age effect: Larger vocabulary size may be related to stronger lexical representations that are more difficult to inhibit because of their higher level of activation. On the basis of our findings, there is a clear need for further research to clarify these relationships. The Interference × Vocabulary and the Interference × SLI interactions provided further motivation for Experiment 2, where we examined whether proactive interference was related to the strength of word representations.

As referenced in the introduction, Morton and Munakata (2002) suggest that proactive interference may occur if the working memory representation of a previous item is stronger than that of the current item. This hypothesis, as another possible cause for poor resistance to proactive interference in children with SLI, was examined in Experiment 2 of the current study.

In summary, the findings from Experiment 1 suggest that a conflict situation (interference condition) has a negative effect on all children's performance accuracy but that this negative effect is larger in children with SLI than in TLD children. Everyone showed an increase in RT in the interference condition compared with the baseline, and this increase was comparable across groups. Younger children were slower than the older participants in each condition.

Experiment 2

In Experiment 2, we examined dynamic interactions between working memory and interference in greater detail. We specifically aimed to clarify whether manipulations designed to strengthen representations in working memory increased children's susceptibility to proactive interference on subsequent task items. According to Morton and Munakata (2002), successive repetitions of an item within a category should increase the strength of that item's representation within working memory and make it more difficult to inhibit the same response on the following trial because of interference. First, we examined how practice strengthens word representations and then how the strength of a previous response impacts performance on the following item. Repetition of an item facilitates the cognitive system to be more fine-tuned for that particular item. Response to the item following the repeated item typically shows increased RT because the cognitive system is less prepared for the non-repeated item, and increased inhibition is required to overcome proactive interference (Rogers & Monsell, 1995). We expected that children would show more difficulty responding to the item immediately following a highly practiced item based on the principle that words with stronger activation—because of repetition—have a greater probability of selection (Gershkoff-Stowe, 2002). Thus, words with strengthened representations leave strong memory traces that interfere with the following stimuli. Given previous evidence of working memory deficits in children with SLI, we expected these children to take longer to build strong working memory representations but were interested in seeing how their resistance to proactive interference would vary as memory traces in working memory became stronger. We tested the following hypotheses in Experiment 2:

1. Children with SLI will need more repetition of the target items to strengthen their word representations than their TLD peers. Their ACC (Hypothesis 1a) and RT (Hypothesis 1b) measures on the repeated items will differ from both language- and age-matched controls.

2. Children with SLI will make more errors on the items following the repeated items than the control groups because of their weakness in inhibition.

3. Responses to the items following repeated items will show increased RT in all groups because it is more difficult to inhibit the representation of a practiced item.

As the strength of representations of the repeated items increases, the RTs for the following items will increase as well.

Method

Participants—Participants included the three groups of children described in Experiment 1 (see Table 1).

Procedure and stimuli—Experiment 2 examined how repeated presentation of items within a category affects postrepetition responses (i.e., ACC and RT for items that followed the repeated items). To examine this effect, we presented participants with six target items (in six different 14-item blocks) four times. Performance measures were compared for the three repeated items (second, third, and fourth presentation) as well as for the three postrepetition items. Baseline performance was measured using items matched on serial position in an identical task that did not involve repetition. Children were not informed that certain items were repeated and were instructed to perform the task in the usual manner, as described above.

Results

Accuracy on repeated items—We assumed that accuracy at repetition *r* for subject *j* was a function of a systematic growth curve plus random error. The repetition variable was coded 0–3, with 0 representing the item's first appearance and 3 representing its fourth appearance (third repetition). This coding lent substantive meaning to each parameter of the growth rate. Visual inspection of individual trajectories indicated a possible curvilinear relationship between repetition and outcome; we therefore included both a linear term (learning rate) and quadratic term (acceleration) for the repetition variable. The model with the quadratic term showed a significantly better fit to the data than the model with only the linear term, $\chi^2(1) = 4.85$, $p = .028$.

Baseline performance accuracy was entered to control for learning or fatigue effects and was calculated by using nonrepeated items that were drawn from an identical task without repetition and that were matched on serial position with repeated items. Subject-level covariates were entered to build the Level 2 model. Vocabulary (raw scores) and non-verbal IQ yielded a better fit, $\chi^2(2) = 13.08$, $p = .001$; but their interactions with the repetition variable did not: for vocabulary, $\chi^2(1) = 1.26$, $p = .533$; for nonverbal IQ, $\chi^2(2) = 0.19$, $p = .91$. Including effects of group variables, SLI, $\chi^2(1) = 0.97$, $p = .325$, and TLD-L, $\chi^2(1) = 0.28$, $p = .595$, on accuracy at $r = 0$ did not improve the model fit; however, SLI, $\chi^2(1) = 4.07$, $p = .043$, but not TLD-L, $\chi^2(3) = 1.41$, $p = .704$, did interact with the linear and quadratic terms of the repetition variable.

On the basis of the above findings, we selected the model shown in Table 3 as best fit to the data (Figure 2A). When controlling for baseline performance, nonverbal IQ, and vocabulary, estimated average accuracy at $r = 0$ was .83, and no group effect emerged. The linear component of the repetition variable showed an instantaneous learning rate of .072 for TLD children at $r = 0$, indicating that average learning rate produced an estimated 8.6% increase in accuracy for these children. The mean acceleration (coefficient of the quadratic term) was negative (−.02) and significant, indicating that TLD children, on average, learned at a decreasing rate over repetition.

Visual inspection of individual trajectories suggested that the marked decrease in accuracy at $r = 2$ and $r = 3$ (see Figure 2A) was mainly attributable to TLD-L rather than to TLD-A children, although the model did not detect this group difference. Learning rate for children with SLI at $r = 0$ was slower than that for TLD children (see negative coefficient of the interaction Repetition × SLI in Table 3): .072 − .062 = .01. This corresponds to a 1.2% predicted increase in accuracy at $r = 0$. Mean acceleration in SLI is −.02 + .025 = .005. This positive, although small, value indicates that children with SLI learned at an increasingly faster rate over multiple repetitions. Estimated learning rate is .02 (+ 2.3%) at $r = 1$; .03 (+ 3.4%) at $r = 2$; and .04 (+ 4.3%) at $r = 3$.

Of greatest theoretical interest is the learning rate at $r = 0$, which mainly captures the effect of the first repetition on performance accuracy and differentiates TLD children, who showed an 8.6% increase in accuracy, and children with SLI, who showed an increase of only 1.2%. The mean acceleration suggests that children with SLI show similar improvement in performance accuracy but do so more gradually, requiring between two and three repetitions to achieve the same increase in performance accuracy that TLD children achieve in a single repetition. This finding supports Hypothesis 1a, which predicted that children with SLI would need more repetitions to strengthen word representations compared with TLD peers.

RT for repeated items—After estimating the null model, we added linear and then quadratic terms of the repetition variable to the model. Consistent with visual inspection of individual trajectories, the linear term yielded a better fit, $\chi^2(1) = 10.32$, $p = .001$; whereas the quadratic term did not and was therefore discarded, $\chi^2(1) = 0.5$, $p = .478$. Baseline RT was then entered to control for baseline performance.

Having identified an adequate Level 1 model, we proceeded to test subject-level predictors. After controlling for effects of nonverbal IQ and vocabulary, we tested the effect of group. The group factor variables SLI and TLD-L did not affect performance at $r = 0$, $\chi^2(1) = 0.8$, $p = .372$, and $\chi^2(1) = 0.11$, $p = .736$, respectively; and did not moderate the effect of repetition number on RT: for SLI, $\chi^2(1) = 0.89$, $p = .346$; for TLD-L, $\chi^2(1) = 0.78$, $p = .376$. On the basis of the final model selected (see Table 3 and Figure 2B), estimated RT at $r = 0$ was 1,221 ms, and estimated repetition effect for all groups (when nonverbal IQ and vocabulary were controlled for) was an RT decrease of 35 ms for each repetition, which corresponds to an estimated benefit of 2.9% decrease in RT. Unlike ACC results, the comparable repetition benefit in RT across groups does not support Hypothesis 1b, which predicted that children with SLI would require more repetitions than TLD children to show a performance benefit.

Accuracy on postrepetition items—To facilitate meaningful interpretation of estimates and control for individual differences in baseline performance, we rescaled variables by subtracting baseline performance ($r = 0$) from performance at Repetitions 1, 2, and 3, with resulting variables indexing the difference between performances on each repetition compared with baseline. As described above, we built the Level 1 model by entering baseline performance, followed by linear and quadratic terms of accuracy on repeated items,

$\chi^2(2) = 23.58$, $p < .001$. The quadratic term was entered as inspection of individual trajectories suggested a possible curvilinear relationship between accuracy of repeated and postrepetition items.

The baseline variable consisted of items matched on serial position with items of the outcome variable, allowing us to control for confounding factors unrelated to the experimental manipulation. Next, subject-level predictors were entered to build the Level 2 model. After entering the two covariates to control for nonverbal IQ and vocabulary, we tested the group effect on the intercept (no repetition benefit), and this was significant: for SLI, $\chi^2(1) = 11.2$, $p < .001$; for TLD-L, $\chi^2(1) = 11.18$, $p < .001$. We subsequently modeled effects of the linear and quadratic terms of repeated item accuracy on the outcome variable (postrepetition accuracy). Only the SLI group moderated the effect of the quadratic term, $\chi^2(1) = 5.65$, $p = .017$. The model shown in Table 4 provided the best fit to the data (see also Figure 2C). As indicated by the linear component of repetition ACC, representation strength of repeated items showed no effect on postrepetition accuracy when repetition ACC was at baseline level (i.e., no repetition benefit). The quadratic term, however, was highly significant, indicating that the effect of repetition ACC on postrepetition ACC increases with increasing performance on repetition ACC. This effect is moderated by the SLI group so that the negative effect of the repetition benefit on postrepetition ACC increases to a greater extent in the SLI group than in the TLD groups (Figure 2C).

In other words, at comparable repetition benefits, there was a greater negative effect on postrepetition items in the SLI group than in the TLD groups, and this group difference increased as repetition benefit increased. This finding partially supports Hypothesis 2, which predicted more post-repetition errors in the children with SLI compared with the control groups.

RT for postrepetition items—Variables were rescaled using the procedure described for accuracy. Visual inspection of individual trajectories indicated a possible curvilinear relationship between repetition effect and postrepetition RT, which seemed to be mediated by group. No group effects were found on the intercept, indicating no between-group RT differences on postrepetition items for repetition benefit = 0: for SLI, $\chi^2(1) = 1.75$, $p = .186$; for TLD-L, $\chi^2(1) = 0.08$, $p = .774$. We proceeded modeling the effect of the linear and the quadratic terms of the repetition benefit RT variable. Three cross-level interactions improved the fit to the data: SLI × Rep-Benefit (repetition benefit) and SLI × Rep-Benefit^2 (repetition benefit squared), $\chi^2(2) = 9.99$, $p = .006$; and TLD-L × Rep-Benefit^2, $\chi^2(1) = 4.49$, $p = .034$. The best fit to the data was therefore the model shown in Table 4 and Figure 2D. The final model shows that, as found in accuracy data, RT of repeated items did not affect postrepetition RT when the RT of repeated items was at the baseline level. Unlike accuracy data, the interaction results indicate that the negative effect of repetition on the response to the following item was more immediate in children with SLI than in their peers.

Overall, repetition benefit had a small effect on postrepetition items in TLD-L, with a minor decrease in postrepetition performance for increasing strength of representation. When repetition benefit was small, its effect on postrepetition performance was significantly greater for children with SLI than for TLD children; however, when repetition benefit was larger, it affected postrepetition performance similarly in both the SLI and TLD-A groups (Figure 2D). Hypothesis 3 was thus partially supported: Repetition benefit had an overall negative effect on the three groups of participants but affected each group somewhat differently.

Discussion

The main goal of Experiment 2 was to examine how strengthening the representations of specific items affects response ACC and RT of the following items. It is more difficult to resist interference following a well-practiced item because the representation of a practiced item is stronger than that of a nonrepeated item (Morton & Munakata, 2002). We examined two aspects of this interaction. First, we were interested in whether children with SLI needed more practice than their peers to strengthen their representations. The second question was whether children across groups differ in the degree to which strengthened representations impact responses to the following items. More specifically, we examined whether children with SLI are less resistant to pro-active interference when response ACC depends more strongly on good inhibition abilities.

Regarding our first question, ACC results showed that children with SLI needed more repetions of the same item to show strengthened representations than did children in both control groups. Performance accuracy for the TLD groups increased immediately following the repetition of a particular item, whereas children with SLI needed more repetitions to show similar ACC increases. Reaction time showed a gradual decrease with each repetition for all groups. Thus, there was a dissociation between ACC and RT during the first few repetitions for the children with SLI, with RT showing more immediate changes than ACC. This finding suggests that these children noticed when an item was repeated but needed more practice than their peers to improve their ACC rate. This finding may be explained on the basis of task sensitivity in children with SLI (Edwards & Lahey, 1998). The authors proposed that children with SLI may need to work harder than their peers to form the same representations. Thus, their poor performance may not necessarily reflect more constrained working memory capacity but may show that these children need more effort to achieve the same goals as their peers. By working harder, children with SLI may overload their system, however.

The literature on implicit learning in children with SLI is limited, but Tomblin and colleagues reported a similar pattern of results to our findings on sequence learning (Tomblin, Mainela-Arnold, & Zhang, 2007). In an experiment using serial reaction time learning, adolescents with SLI showed slower learning rates than the controls. The authors suggested that in the initial phases of learning new patterns, the representations are less stable in children with SLI compared with TLD peers. This instability may be related to poor suppression of competing items.

It is well known that error production is influenced by task demands. Complex tasks require stronger representations. More limited representations might be sufficient for simple tasks (Stedron, Sahni, & Munakata, 2005). That is indeed what our data on the baseline measures suggest. There was no group difference in the baseline measures between the children with SLI and their age-matched peers, but in a more demanding condition, where the repetition of a previous item resulted in more interference at the following item, children with SLI showed poorer performance than their peers. Thus, regarding our second question, which related to group differences in postrepetition responses, results suggest that the strengthening of an item’s representation has a larger negative effect on response accuracy of the following item in children with SLI than in those with TLD. According to the active versus latent representations model (Morton & Munakata, 2002), behavioral flexibility can be interpreted on the basis of the relations between active and latent memory traces. If the active representation is weak, then the latent traces will interfere with it. Our outcomes indicate that the representations of the repeated items were stronger than that of the following items; therefore, the practiced items interfered with the current items, particularly in children with SLI.

The overall RT data showed the expected pattern: Repetition of an item resulted in decreased RT but caused an increase in RT for the items following the repeated ones. This phenomenon is similar to the switch cost effect in task switching paradigms. The increase in RT for the item following a repeated item reflects the extra time needed to reconfigure the cognitive system (Meiran, 1996) and may also indicate carryover from the previous trial (Hsieh & Liu, 2005).

In summary, children with SLI needed more repetition than their peers to strengthen their representations of given items. Thus, the implicit learning rate of children with SLI was slower than that of the children with TLD. Children with SLI needed more effort to strengthen the representations of the repeated items. Once the representations of the practiced items became stronger, a larger interference effect was observed on the following items in children with SLI compared with TLD controls. This finding suggests that children with SLI showed more difficulty than the controls with items that required stronger inhibition. The practiced items interfered with the following items to a greater extent in children with SLI than in TLD children.

General Discussion

Our aim was to examine how different experimental manipulations affect children’s resistance to proactive interference. Previous research on executive functions in children with SLI typically used complex neuropsychological tests that provided global scores for various executive functions. We used a new information processing battery that we have developed over the years in our laboratory to systematically investigate different executive functions, including working memory, attention switching, and different inhibition components. The tasks in the two experiments were similarly structured but consisted of different experimental manipulations.

The overall finding was that children with SLI showed less efficient resistance to proactive interference under each condition. Results from Experiment 1 indicated that children with SLI performed similarly to their peers in the baseline condition, where minimal interference occurred. With an increase in interference, however, children with SLI showed a larger performance decline than their peers. All children were negatively affected by the increase in interference, as shown in their decreased accuracy rate, but the change from the baseline was greater in the group of children with SLI than in children with TLD. Children with SLI showed a larger interference effect than the controls. There are different interpretations for the finding that children with SLI often did not reject previously relevant but currently irrelevant items. According to the activation and binding theory of Oberauer and Lange (2009), children might have responded to particular items on the basis of their familiarity. Familiarity arises from an item’s activation level. If children with SLI kept previous items active during subsequent trials, then previous target items might have seemed relevant on the basis of their high familiarity even when they became distractors.

Inhibition theories provide an alternative explanation. To prevent the buildup of proactive interference from successive trials, it is important to suppress information that is no longer relevant (Lustig, May, & Hasher, 2001). There is evidence in the literature that children with SLI have difficulty suppressing previous information (Marton et al., 2007; Norbury, 2005; Spaulding, 2010). Results of Experiment 1 further support this finding. However, future research is needed to decide whether too much activation of irrelevant information or poor inhibition is more responsible for the weak resistance to proactive interference in children with SLI. It is important to acknowledge, however, that these two mechanisms—activation and inhibition—are closely related to each other.

In Experiment 2, we explored how the strength of working memory representations interacts with proactive interference by studying the effect of practice on response accuracy to subsequent items. Specifically, we investigated whether children with SLI need more repetition of a particular item to strengthen its representations and whether strong memory representations have a negative effect on the following items. The ACC results showed that children with SLI needed more repetition than their peers to strengthen representations, and once representations became strong, they negatively affected performance on the following items. On the basis of findings from neurophysiologic studies, this result may reflect an important underlying problem at the neuronal level. Practice leads to a plastic change in information processing that can be measured by performance ACC, which increases, and RT, which decreases. These behavioral changes are strongly associated with changes in the neuronal network. As a result of practicing, the activity in the network declines. The magnitude of this change is a strong indicator of individual variations in information processing capacity (Ramsey, Jansma, Jager, Van Raalten, & Kahn, 2004). When performing a novel task, there is no direct coupling between the stimulus and the response; therefore, a relatively large number of neurons need to be recruited. When coupling is achieved through practice, only neurons with a relevant role remain active; others disengage from processing, which results in a liberation of processing resources. This account is similar to Oberauer and Lange’s (2009) binding theory. Children with SLI may show less efficient coupling between the stimulus and response or weak content context bindings that result in accumulation of information in working memory. A cluttered working memory may cause weak resistance to proactive interference. Future research is needed to examine systematically whether children with SLI form appropriate content context bindings during information processing.

In summary, the current results suggest that children with SLI show weaker resistance than their peers to proactive interference. These children show difficulty with suppressing irrelevant information when task goals change, they make significantly more interference errors than do typically developing children, and they show a slower rate of implicit learning. Whether the core of the problem is related to a failure to inhibit previous information, to a failure to activate strongly enough current representations, or to a weakness in forming appropriate content context bindings is a question for future research. The current study provides supporting evidence for both major theories that attempt to describe the nature of proactive interference control. The findings from Experiment 1 support the inhibition theories (e.g., Hasher et al., 2007) suggesting that inefficient suppression of irrelevant information results in poor resistance to proactive interference. The findings from Experiment 2, however, support the active versus latent working memory representation model (Morton & Munakata, 2002), suggesting that it is more difficult to resist interference following a strong item, such as a well-practiced item, than an item with weaker representation. The present study suggests that resistance to proactive interference is a complex function, and its deficit may indicate problems in different underlying mechanisms. Children with SLI show a weakness in both suppressing irrelevant information and strengthening their working memory representations. On the basis of these findings, there is an urgent need for developing intervention methods that are process driven, promote strategy use, facilitate discrimination between relevant and irrelevant information, foster the suppression of irrelevant material, and help children to focus on task-relevant items because all these functions play an important role in language comprehension and production.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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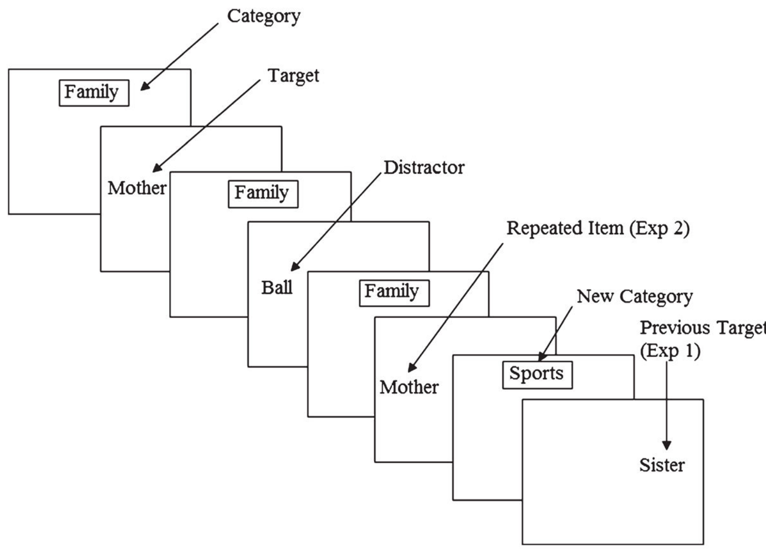

Figure 1.
Paradigm for Experiments (Exp) 1 and 2.

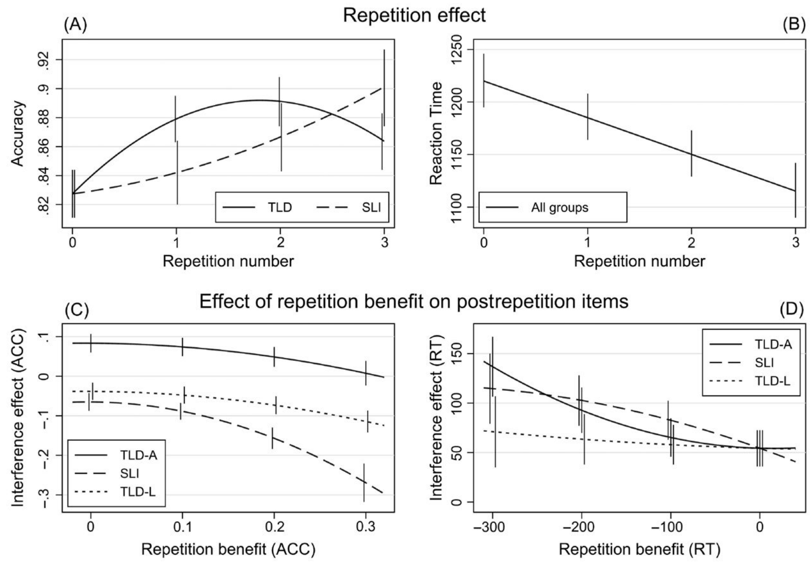

Figure 2.

Effects of repeated items and effects of repetition benefit on postrepetition items. Error bars represent standard error. ACC = accuracy; RT = reaction time.

Table 1

Descriptive characteristics of the study participants.

Characteristic	SLI (*n* = 22)	TLD-A (*n* = 22)	TLD-L (*n* = 22)
Gender (male/female)	13/9	11/11	7/15
Age in months	147 (15.6)	150 (22.9)	117 (18.7)
TONI–3 standard score	101.3 (14.8)	111 (17.2)	103.7 (9.9)
CELF–4 Core Language standard score	81.6 (13.8)	119.4 (9.5)	99.4 (11.2)
CELF–4 Recalling Sentences raw score	57.1 (13.2)	83.2 (4.6)	60.4 (8.9)
EOWPVT standard score	88.3 (13.7)	107.5 (14.8)	102.8 (9.8)
TROG–2 standard score	88.3 (12.1)	106.2 (7.2)	96.5 (10.7)
Working memory: verbal sequencing perseverative errors	8.2 (4.4)	4.2 (2.8)	4.7 (2.8)

Note. Except for gender, all data are means (with standard deviations). SLI = specific language impairment; TLD-A = age-matched children with typical language development; TLD-L = language-matched children with typical language development; TONI–3 = Test of Nonverbal Intelligence, Third Edition; CELF–4 = Clinical Evaluation of Language Fundamentals, Fourth Edition; EOWPVT = Expressive One-Word Picture Vocabulary Test; TROG–2 = Test for Reception of Grammar: Version 2.

Table 2

Interference effect: Summary of linear mixed-effects final models for performance accuracy and reaction time.

Variable	Coefficient or variance[a] (*SE*)	*z*	*p*	95% CI
	Accuracy			
Fixed effects				
Intercept	0.842 (0.012)	72.39	<.001	[0.819, 0.865]
Interf	−0.048 (0.011)	−4.38	<.001	[−0.069, −0.026]
NV IQ	0.002 (0.002)	1.41	.16	[−0.001, 0.005]
Vocab	0.002 (0.001)	2.82	.005	[0.001, 0.003]
Interf × Vocab	−0.001 (0.001)	−2.9	.004	[−0.002, −0.001]
Interf × SLI	−0.05 (0.019)	−2.73	.006	[−0.087, −0.014]
Variance components				
Intercept	0.006 (0.001)			[0.004, 0.01]
Residual	0.003 (0.001)			[0.002, 0.004]
	Reaction time (ms)			
Fixed effects				
Intercept	1,343.87 (37.54)	35.79	<.001	[1270.28, 1417.45]
Interf	45.96 (19.22)	2.39	.017	[8.29, 83.63]
NV IQ	−1.78 (4.42)	−0.4	.687	[−10.45, 6.89]
Vocab	−6.32 (1.83)	−3.45	.001	[−9.91, −2.73]
Interf × Vocab	2.43 (1.04)	2.33	.02	[0.38, 4.47]
TLD-L	215.33 (65.79)	3.27	.001	[86.39, 344.28]
Variance components				
Intercept	49,101.4 (9,668.4)			[33379.9, 72227.2]
Residual	12,190.3 (2,122.3)			[8666, 17147.8]

Note. CI = confidence interval; Interf = interference condition; NV IQ = nonverbal IQ (TONI–3); Vocab = Vocabulary (raw scores, EOWPVT).

[a]For fixed effects, the data given are coefficients; for variance components, variance.

Table 3

Repeated presentation of items effect: Summary of linear mixed-effects final models for performance accuracy and reaction time.

Variable	**Coefficient or variance[a] (*SE*)**	***z***	***p***	**95% CI**
	Accuracy			
Fixed effects				
Intercept	0.827 (0.015)	53.79	<.001	[0.797, 0.858]
Rep (learning rate)	0.072 (0.026)	2.77	.006	[0.021, 0.122]
Rep^2 (acceleration)	−0.02 (0.008)	−2.34	.019	[−0.036, −0.003]
Baseline	0.084 (0.052)	1.63	.104	[−0.017, 0.185]
NV IQ	0.004 (0.001)	2.87	.004	[0.001, 0.007]
Vocab	0.001 (0.0004)	3.19	.001	[0.001, 0.002]
Rep × SLI	−0.062 (0.024)	−2.57	.01	[−0.109, −0.015]
Rep^2 × SLI	0.025 (0.01)	2.38	.017	[0.004, 0.045]
Variance components				
Intercept	0.007 (0.002)			[0.004, 0.011]
Residual	0.011 (0.001)			[0.009, 0.014]
	Reaction time (ms)			
Fixed effects				
Intercept	1,220.6 (25.92)	47.1	<.001	[1169.8, 1271.4]
Rep (learning rate)	−34.915 (9.57)	−3.65	<.001	[−53.673, −16.157]
Baseline	0.225 (0.44)	5.06	<.001	[0.138, 0.312]
NV IQ	−4.389 (3.2)	−1.37	.17	[−10.657, 1.879]
Vocab	−1.061 (1.3)	−0.81	.421	[−3.642, 1.521]
Variance components				
Intercept	23,205 (5,573.8)			[14491, 37156]
Residual	30,071 (3,050.7)			[24649, 36686]

Note. Rep = repetition number (0–3); Rep^2 = repetition number squared (0–9).

[a]For fixed effects, the data given are coefficients; for variance components, variance.

Table 4

Effect of repetition benefit on postrepetition items: Summary of linear mixed-effects final models for performance accuracy and reaction time.

Variable	Coefficient or variance[a] (*SE*)	*z*	*p*	95% CI
	Accuracy			
Fixed effects				
Intercept	0.084 (0.023)	3.58	<.001	[0.038, 0.129]
Baseline	−0.01 (0.043)	−0.23	.82	[−0.093, 0.074]
Rep-benefit (ACC)	−0.015 (0.068)	−0.23	.821	[−0.149, 0.118]
Rep-benefit^2 (ACC)	−0.794 (0.262)	−3.03	.002	[−1.309, −0.28]
NV IQ	0 (0.002)	0.21	.836	[−0.003, 0.004]
Vocab	−0.001 (0.001)	−1.05	.293	[−0.002, 0.001]
SLI	−0.149 (0.035)	−4.28	<.001	[−0.217, −0.081]
TLD-L	−0.122 (0.034)	−3.61	<.001	[−0.188, −0.056]
SLI × Rep-Benefit^2	−1.426 (0.596)	−2.39	.017	[−2.595, −0.257]
Variance components				
Intercept	0.0041 (0.0015)			[0.002, 0.0082]
Residual	0.0157 (0.0016)			[0.0129, 0.0192]
	Reaction time (ms)			
Fixed effects				
Intercept	54.367 (18.59)	2.92	.003	[17.914, 90.821]
Baseline	0.051 (0.037)	1.37	.172	[−0.022, 0.123]
Rep-benefit (RT)	−0.026 (0.093)	−0.28	.78	[−0.208, 0.156]
Rep-benefit^2 (RT)	0.001 (0)	2.9	.004	[0, 0.001]
NV IQ	−2.642 (2.566)	−1.03	.303	[−7.672, 2.388]
Vocab	−0.03 (1.037)	−0.03	.977	[−2.062, 2.002]
SLI × Rep-Benefit	−0.298 (0.139)	−2.15	.031	[−0.57, −0.027]
SLI × Rep-Benefit^2	−0.001 (0)	−3.65	<.001	[−0.002, −0.001]
TLD-L × Rep-Benefit^2	−0.001 (0)	−2.13	.033	[−0.001, 0]
Variance components				
Intercept	8,436.4 (3,641.9)			[3619.9, 19661.4]
Residual	43,945.5 (4,444.5)			[36043.4, 53580]

Note. Rep-benefit = repetition benefit; Rep-benefit^2 = repetition benefit squared.

[a]For fixed effects, the data given are coefficients; for variance components, variance.