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Lexical Activation during Sentence Comprehension in Adolescents with History of Specific Language Impairment

Arielle Borovsky, Ph.D.¹, Erin Burns, M.A.², Jeffrey L. Elman, Ph.D.², and Julia L. Evans, Ph.D.^{2,3}

¹Department of Psychology, Florida State University, Tallahassee, FL

²Center for Research in Language, University of California, San Diego, La Jolla, CA

³School of Behavioral and Brain Sciences, University of Texas at Dallas, Richardson, TX

Abstract

One remarkable characteristic of speech comprehension in typically developing (TD) children and adults is the speed with which the listener can integrate information across multiple lexical items to anticipate upcoming referents. Although children with Specific Language Impairment (SLI) show lexical deficits (Sheng & McGregor, 2010) and slower speed of processing (Leonard et al., 2007), relatively little is known about how these deficits manifest in real-time sentence comprehension. In this study, we examine lexical activation in the comprehension of simple transitive sentences in adolescents with a history of SLI and age-matched, TD peers. Participants listened to sentences that consisted of the form, Article-Agent-Action-Article-Theme, (e.g., *The pirate chases the ship*) while viewing pictures of four objects that varied in their relationship to the Agent and Action of the sentence (e.g., Target, Agent-Related, Action-Related, and Unrelated). Adolescents with SLI were as fast as their TD peers to fixate on the sentence's final item (the Target) but differed in their post-action onset visual fixations to the Action-Related item. Additional exploratory analyses of the spatial distribution of their visual fixations revealed that the SLI group had a qualitatively different pattern of fixations to object images than did the control group. The findings indicate that adolescents with SLI integrate lexical information across words to anticipate likely or expected meanings with the same relative fluency and speed as do their TD peers. However, the failure of the SLI group to show increased fixations to Action-Related items after the onset of the action suggests lexical integration deficits that result in failure to consider alternate sentence interpretations.

Keywords

SLI; sentence comprehension; eye tracking

1. Introduction

Successful spoken communication depends on the listener's ability to rapidly interpret and integrate the meaning of multiple words as a sentence unfolds. For the listener to succeed at this task, many aspects of lexical processing must be coordinated simultaneously. For instance, listeners must segment and decode the rapidly decaying acoustic signal into words. They also must activate and/or retrieve the correct lexical information from semantic memory and then hold onto the accumulating information as the sentence unfolds. In typically developing (TD) children and adults, these abilities interact rapidly to allow listeners to update their understanding of ongoing sentences continuously and to generate expectations about upcoming lexical items within the sentence. Children with Specific Language Impairment (SLI) have significant difficulty with many of these underlying lexical processing skills. In this study, we explore how adolescents with a history of SLI integrate meaning across multiple spoken words to comprehend sentence in real time, using a visual world eye-tracking paradigm.

The term *Specific Language Impairment*, introduced by Stark and Tallal (1981), refers to a diagnosis in children who have difficulty acquiring and using language in the absence of any clear etiology (e.g., hearing loss, intellectual impairment, neurological involvement). Language difficulties in these children include delayed onset and slower acquisition of lexical and grammatical forms, smaller vocabularies, and difficulty acquiring and using inflectional morphology and complex syntax (Leonard, 1998). Children with SLI have a multitude of linguistic and non-linguistic deficits, including difficulties in understanding words and sentences. Although there are several competing accounts of the etiology of SLI, there is a growing body of work that suggests that the language deficits seen in SLI are secondary to impaired nonverbal cognitive processing factors, such as speed of information processing and/or working memory capacity (e.g. Ellis Weismer, et al., 1999; Gillam, et al., 1998; Hoffman & Gillam, 2004; Leonard, et al., 2007; Montgomery & Evans, 2009; Montgomery, 2000). These domain-general accounts of SLI contrast with other proposals that characterize language deficits in (at least some groups of) children with SLI as domain-specific, arising primarily from a specific difficulty with acquisition or usage of grammatical aspects of language, such as tense marking, verb agreement, object clitics, or more hierarchically structured grammatical forms (Clahsen, et al., 1997; Paradis, et al., 2006; Rice, et al., 1995; van der Lely, 2005).

While much of the research in SLI has focused on morpho-syntactic deficits, lexical abilities are compromised as well (Alt & Plante, 2006; Alt, et al., 2004; Capone & McGregor, 2005; Lahey & Edwards, 1999; Leonard, et al., 1983; McGregor & Appel, 2002; McGregor, et al., 2002; McGregor & Waxman, 1998; Seiger-Gardner & Schwartz, 2008). For example, in novel-word learning studies, children with SLI require more exposure trials to link novel words to meaning as compared to typical peers (Alt & Plante, 2006; Alt, et al., 2004; Gray, 2003; Gray, 2004; Rice, et al., 1992; Rice, et al., 1994). They also have significant difficulty learning the semantic features of novel words and appear to attend to qualitatively different semantic features of novel objects as compared to their TD peers (Alt & Plante, 2006; Alt, et al., 2004). Further, it appears that the semantic/conceptual representations of children with SLI are poorly differentiated, which results in weaker activation or priming of semantic

associations between highly familiar lexical items as compared to typical children (Lahey & Edwards, 1999; Mainela-Arnold, et al., 2010; Mainela-Arnold, et al., 2010; McGregor, 1997; Sheng & McGregor, 2010).

Children with SLI are also slower and less accurate than are their TD peers across a range of lexical processing tasks involving known items, including lexical decision tasks (Crosbie, et al., 2004; Edwards & Lahey, 1996; Windsor & Hwang, 1999) and rapid automatic picture naming (Edwards & Lahey, 1996; Lahey & Edwards, 1999; Leonard, et al., 1983). In gated lexical identification tasks, children with SLI require more time than do their TD peers to identify known words in isolation (Mainela-Arnold, et al., 2008; Marshall & van der Lely, 2008). Finally, children with SLI are also slower than their typical peers to identify and retrieve the meanings of words embedded in ongoing sentences (Montgomery, 2002, 2004, 2005, 2006).

Historically, slower lexical processing in SLI has been viewed as part of a larger domain-general deficit in speed of processing (see Leonard et al., 2007, for a detailed discussion) but there is recent evidence that slower real-time lexical access in children with SLI may result from degraded and/or underspecified lexical representations. In particular, it appears that these poorly specified lexical representations in children with SLI increases their vulnerability to retrieval interference effects and to lexical cohort competition, which results in slower and less efficient lexical processing in these children as compared to TD children (e.g. Coady & Evans, 2008; Crosbie, et al., 2004; Evans, 2002; Joanisse & Seidenberg, 1998; Lahey & Edwards, 1996; Mainela-Arnold, et al., 2008). Moreover, this inefficiency in lexical processing appears to be related to the slower retrieval and integration of the lexical-semantic properties of incoming words into a developing sentence meaning in children with SLI (Montgomery, 2006).

There are methodological challenges to examining the relationship between lexical processing deficits and sentence processing in children with SLI, however. Research paradigms that use *offline* designs assess sentence comprehension at some point after the sentence is completed. In contrast, *online* comprehension methods that measure words as they are spoken allow for a tighter link between real-time lexical processing and sentence comprehension. Studies that use *online* paradigms like speeded word identification as an index of processing in varying sentence contexts have provided an understanding of the fluency with which children with SLI can understand single words in a variety of sentential conditions (e.g. Montgomery & Evans, 2009; Montgomery, 2004, 2006; Stark & Montgomery, 1995). While these *online* methods provide a more detailed window into sentence comprehension, single-word identification paradigms do not allow for the examination of the continuous changes in lexical activation as it builds over the course of a sentence.

Both *offline* and *online* methods that rely on a behavioral response on the part of the child face an additional problem, specifically, that children with SLI may have significant difficulty with motor coordination tasks and have slower manual motor responses than normally developing peers (Chuang, et al., 2011; Hill, 1998, 2001; Rechetnikov & Maitra, 2009; Webster, et al., 2005). Therefore, to examine continuous changes in *online* lexical

activation during sentence processing in children with SLI, it is necessary to use a method that does not require a manual motor response.

Two such techniques are event-related brain potentials (ERPs) and eye-movement paradigms. Both of these methods can index real-time interpretation of language without requiring a manual response on the part of the participant. ERP methods have been used to examine lexical processing in children with and without SLI (Mills & Neville, 1997; Neville, et al., 1993; Sabisch, et al., 2006). Although these studies have provided insight into the nature of lexico-semantic processing of single words within sentences for children with SLI, the paradigm does not easily facilitate the continuous measurement of multiple lexico-semantic competitors across the entire time-course of a sentence.

In contrast, eye-tracking methodology that uses the visual-world paradigm (VWP: Tanenhaus, et al., 1995) is better suited to this type of investigation and allows for the tracking of moment-to-moment changes in lexical activation in response to spoken language (e.g. Allopenna, et al., 1998; Kukona, et al., 2011; Yee & Sedivy, 2006). The paradigm involves the measurement of participants' gaze to various objects in a visual scene in response to spoken language (Huettig, et al., 2011 for a review). Changes in participants' visual fixation patterns in regard to the scene reflect moment-to-moment comprehension of language as it unfolds in real time. The paradigm, which is sensitive to participants' eye movements to target scenes even before a target word is spoken, also allows for the detection of participants' anticipation of upcoming information (Allopenna, et al., 1998; Dahan, et al., 2001).

Findings from numerous eye-tracking studies suggest that listeners continuously and incrementally update their ongoing interpretation of the speech signal by using many sources of linguistic and non-linguistic information. This is an active process; listeners use this information to generate predictions about likely sentence continuations at multiple linguistic levels (Altmann & Kamide, 1999; Altmann & Kamide, 2007; Arnold, et al., 2000; Kamide, et al., 2003; Lew-Williams & Fernald, 2010; Salverda, et al., 2003; Sedivy, et al., 1999; Tanenhaus, et al., 2000; Tanenhaus, et al., 1995; Trueswell, et al., 1993). Further, because the method does not require a speeded manual response from participants, and the only task requirements are that participants can freely gaze at images as they listen to language, VWP is well suited to measuring rapid processing of ongoing speech in a variety of populations, including individuals with language disorders.

Eye-tracking methods have recently been employed to study lexical processing in individuals with SLI (Andreu, et al., 2012; McMurray, et al., 2010). These studies have revealed considerable similarities as well as qualitative differences in online processing of lexical items of children and adolescents with SLI as compared to typical controls. They have also been important in highlighting the ability of eye-tracking paradigms to characterize mechanisms involved in the comprehension of single words by individuals with SLI. For example, the first eye-tracking study to examine lexical activation during spoken word comprehension in adolescents with SLI (McMurray et. al., 2010), found that participants with poorer language skills showed fewer fixations towards target words and more toward distractor items. The authors concluded that this pattern was best explained by

differences in lexical activation, such as rate of lexical decay, and not by differences in processing speed or capacity.

To investigate more complex language processing tasks that more fully mirror the richness and complexity of everyday language comprehension, however, it is necessary to extend eye-tracking studies and the use of VWP to the sentence level. A logical next-step in this endeavor is to examine lexical processing in simple sentence structures using items that require coordination of lexical meaning across both an agent and an action. Thus, we seek to extend our understanding of the role of lexical processing deficits in real-time sentence interpretation in adolescents with SLI, by measuring lexical activation within (simple) sentences.

In prior research (Borovsky, et al., 2012), we constructed an eye-tracking task whereby adult and child participants heard simple transitive sentences of the form Article-Agent-Action-Article-Theme, such as, *The pirate chases the ship*, while viewing a scene that contained items related to the related to the Agent only (TREASURE), the Action only (CAT), both the Agent and Action (Target: SHIP), or neither the Agent or Action (Unrelated: BONES). Notably, this paradigm allows the researcher to control the relationship of the distractor items to words in the sentence, which enables a clear comparison of the relative activation and anticipation of candidate target meanings in response to the spoken agent and action as the sentence unfolds. On this task, adults and children (aged 3–10 years) show remarkably similar performance: On hearing the sentential Agent (e.g., *pirate*), they look to the Agent-related items; and after hearing the Action (e.g., *chases*), they primarily direct their fixations to the Target item and show a (smaller) rise in looking to the Action-related distractor (CAT). Results from this task show that, based on the information available, children as young as 3 can rapidly integrate across multiple lexical items to generate multiple expectations about upcoming items.

Studies of processing speed in SLI have generally assumed that the slower speed of processing seen in children with SLI is a domain general deficit. Findings from a recent eye-tracking study (Andreu, et al., 2012), however, show that children with SLI are no slower than age-matched peers in their speed of recognition of simple visual stimuli. Unlike age-matched controls, however, they are disproportionately slower in processing three-argument verbs as compared to nouns, and one- and two-argument verbs.

In this study, we extend prior work in a task that employs simple transitive sentences that require the rapid activation and incorporation of information about nouns and verbs across a sentence (Borovsky, et al., 2012). Importantly, the stimuli designed for this task were normed in this prior study to be comprehensible to preschool-aged children. This type of design enabled us to examine moment-to-moment processing in detail in adolescents with SLI and age-matched controls while ensuring high levels of comprehension across the two groups. Because prior work has indicated that children with SLI show impaired comprehension of complex but not simple sentence structures relative to age-matched peers (Montgomery & Evans, 2009), we use simple sentences in our investigation to minimize task demands that may disproportionately affect sentence comprehension in individuals with SLI relative to age-matched peers. This design allows us to examine how lexical activation

proceeds in a task that scales logically from prior studies that explore single word recognition, or coordination of a verb with an object (McMurray et. al, 2010; Andreu et. al. 2012).

Recent eye-tracking studies indicate that it is possible that the looking behavior of the children with SLI reflects a slower speed of lexical processing, especially for verbs (Andreu, et al., 2012). If adolescents with SLI are particularly slow in processing verbs as compared to nouns, we might expect to see slower looking, as compared to TD peers, in response to the sentence-final Target item (SHIP). Alternatively, if SLI is a domain general deficit in speed of processing, we might anticipate that adolescents with SLI would show slower lexical activation across the sentence (Montgomery, 2006), with slower fixation speeds for participants with SLI as compared to typically developing controls (slower speed of lexical activation) to the sentence-final target item (SHIP) as well as to related and unrelated distractors. Alternatively, if individuals with SLI have degraded lexical representations that lead to poorer activation of related meanings (Velez & Schwartz, 2010) or over-rely on event-probable cues to comprehend the sentences (Evans, 2002), we would expect to find no differences in looking at Target items across groups but would expect to see reduced fixations to locally coherent but non-event related distractors (e.g., CAT) in the children with SLI.

In addition to examining moment-by-moment shifts in gaze to large areas of interest on a screen, it is also possible to examine finer spatial distribution of gaze over longer time windows. This type of analysis may provide additional insight into differences in semantic feature analysis or overall attention to the visual scene that are less straightforward to examine with timecourse analyses. We therefore conduct several exploratory analyses of spatial fixation across the visual scene in adolescents with and without SLI during several portions of the sentence.

2. Method

2.1 Participants

A total of 26 adolescents participated in the study, including 12 monolingual English-speaking adolescents (5 females) with a history of SLI (mean age in months = 198, $SD = 26.38$, range = 157–241) and 14 TD adolescents (5 females). All of the adolescents in this study were drawn from the SLI and TD subgroups of a previous project – The San Diego Project in Cognitive and Neural Development (PCND). The PCND project was a longitudinal project established in 1990 to investigate neurodevelopmental disorders in children. The participants in the PCND-SLI group were required to meet the following criteria: 1) documented language impairment, 2) receiving speech and language services, 3) performance IQ (PIQ) of 80 or higher on the WISC-R, WPPSI or Leiter non-verbal measures; 4) no major neurological abnormalities (determined by a neurological examination); 5) expressive language composite score 1.5 or more standard deviations below the mean using the CELF-R (Semel, et al., 1987); and 6) absence of known developmental disorders such as mental retardation or autism. The individuals in the PCND-TD subgroup were required to meet the same criteria with the exception that performance on standardized tests of intelligence, language, and academic functioning were within normal

limits. Similar to the protocol used in the EpiSLI project (e.g., Tomblin, et al., 1997), the participants' inclusion in the SLI and TD groups based on their initial PCND classification criteria was maintained in this project.

Research indicates that there is steady language growth for children with history of SLI between the ages 7 and 17 (Conti-Ramsden, et al., 2012). For the current study, to confirm SLI and TD group membership, all participants completed a battery of standardized tests in addition to the experimental measures. The participants' nonverbal intelligence quotient (IQ) and language abilities were assessed using Leiter-R (Roid & Miller, 1997), the CELF-4 (Semel, et al., 2003), the CASL (Carrow-Woolfolk, 1999), and the CREVT-2 (Wallace & Hammill, 2002). All participants continued to have normal nonverbal intelligence while the language skills for the adolescents with a history of SLI continued to be significantly below those of their age-matched peers having a history of typical language development (Table 1; CELF-4 Formulated Sentences, $t(24)=6.24$, $p<.0001$; CELF-4 Recalling Sentences $t(24)=13.94$, $p<0.0001$; CASL Nonliteral Language, $t(24)=7.12$, $p<.0001$; CASL Meaning from Context, $t(24)=6.67$, $p<.0001$; CREVT Expressive $t(24)=6.09$, $p<.0001$; CREVT Receptive, $t(24)=5.00$, $p<0.0001$). All of the participants also met the following inclusion/exclusion criteria: (a) passed a pure-tone audiometric screening at 20 dB HL at 500, 1000, 2000, and 4000 Hz (American Speech-Language-Hearing Association, 1997); (b) normal or corrected vision according to parental report; (c) normal oral and speech motor abilities, as assessed by a certified speech language pathologist; (d) speech intelligibility of 95% or higher based on spontaneous language sample; and (e) from a monolingual, English-speaking home.

2.2 Materials

Eight sets of image/sentence quartets were selected from a prior study whose participants were between 3 and 10 years of age and college-aged adults (Borovsky et al., 2012). In this prior study, sentence quartets were constructed by crossing two Agents with two Actions to create four sentences. Images corresponded to the sentential themes in the quartet (Figure 1). For example, one quartet crossed the agents (*pirate* and *dog*) with actions (*hides* and *chases*) to result in the following four sentences:

1. The pirate hides the treasure.
2. The pirate chases the ship.
3. The dog hides the bone.
4. The dog chases the cat.

The corresponding Target object images for each sentence would be: TREASURE, SHIP, BONE, and CAT, respectively, and participants would see all four images concurrently. For any individual sentence, each image would correspond to one of the four image conditions (Target, Agent-Related, Action-Related, Unrelated). In a sentence such as, *The pirate hides the treasure*, TREASURE would be the Target image, SHIP would be the Agent-Related image, BONE would be the Action-Related image, and CAT would be the Unrelated image. Across all quartets, each image would appear in each condition once, thus yielding a completely balanced design (Figure 1).

Visual images were 400x400-pixels square, photo-realistic, and typical exemplars of Target items. Borovsky et al. (2012) also conducted several norming experiments to ensure that these stimuli would be recognizable and understandable to young children (aged 3–4) and to determine whether the Agent and Action of the sentence also would generate an expectation of the Target item in young children. Performance on this expectation norming task was also taken as an indication of whether or not the Agent and Action were related to the Target item.

Auditory materials from Borovsky et. al. (2012) were also included in the study. These consisted of 32 transitive sentences (Article 1, Agent, Action, Article 2 and Theme) of equal duration, with each word onset occurring at the same time point in each sentence (see Borovsky et. al. 2012 for description of the duration normalization procedure). The intensity of the stimuli were also normalized to 70db. The sound files were presented to participants via headphones, so that the same stimulus was presented to each ear. The experimental sentences are listed in Appendix A.

Within each version of the study, participants heard 16 of 32 possible sentences. Each quartet of four objects was seen twice, with two out of the four possible sentences for each set presented. The position of the Target image was presented with equal frequency in each quadrant. Across all versions, the position of each object was presented with equal frequency in each quadrant, and, in each version, the Target image appeared in each quadrant an equal number of times.

2.3 Procedure

Participants attended two sessions that were completed at the Center for Research in Language at the University of California, San Diego. During the sessions, participants completed the eye-tracking study and additional standardized language assessment measures. Each session lasted approximately 45 to 60 minutes, and participants were compensated monetarily for their time.

2.3.1 Eye-tracking task—Participants were seated in a stationary chair in front of a 17” LCD display. Stimuli were presented using a PC computer that ran SR Research Experiment Builder software (2011) .

Participants were told that they would be seeing pictures and listening to sentences, and they were instructed to click, using the mouse, on the picture that “goes with the sentence.” They completed one practice trial before starting the study, and for all participants, no further explanation was necessary. A manual 5-point calibration and validation routine, which used a standard black-and-white 20-pixel bull’s-eye image, was performed before the start of the experimental trials. This same bull’s-eye image re-appeared in the center of the screen before the start of each trial. The experimenter initiated the trial when the participant fixated to this location.

Participants viewed a set of four images for 2000 ms prior to sentence onset, and the images remained on the screen after sentence offset until the participant had selected, using the mouse, an image from the array. If necessary, recalibration of the eye tracker was performed

between trials, although this was rarely needed. Participants were given a break halfway through the study. The experimental task lasted 5–10 minutes.

2.3.2 Eye-movement recording—An Eyelink 2000 Remote Eye-tracker with a remote arm configuration at 500 Hz recorded eye movements. Using the remote-arm, we individually adjusted the position of the display and camera to 580–620 mm distance from the participant's face. With the use of a target sticker affixed to the participant's forehead, head and eye movements were automatically tracked by the eye-tracker system, thereby allowing stable tracking even with moderate movement by the participant.

Fixations were recorded in each trial from the onset of the images, until the participant selected an image. Using the eye-tracker's default threshold set, the recorded eye movements were automatically classified as saccades, fixations, and blinks. Offline, the data were binned into 10-ms intervals, on which subsequent analyses were performed.

3. Results

3.1 Approach to Analyses

As described above, our data set consisted of a recording of participants' gaze to four images as they listened to accompanying simple sentences. Our first analyses (Section 3.2) assessed whether or not the participants attended to the task by selecting the appropriate picture that matched the sentential theme. We then carried out a number of analyses to plot and characterize the timing of fixations towards the images in response to the sentences (Section 3.3–3.4). Next we sought to determine whether differences in the latency, timing, or number of fixations may have existed across groups (Sections 3.4.1–3.4.5). Finally, we carried out a set of exploratory analyses to examine how participant's spatial distribution of fixations across larger periods of the sentence may have varied by group (Section 3.4.6).

3.2 Behavioral Accuracy

Participants' ability to select the correct target picture for the sentences was used to confirm that participants in both groups comprehended the sentences. All participants selected the correct picture 100% of the time.

3.3 Time-course measurements

The mean proportion of time that the participants fixated on each of the images was then calculated (Target, Agent-Related, Action-Related, Unrelated) at each 10-ms time window over the sentence duration for all participants with SLI (Figure 2a) and TD participants (Figure 2b). Visual inspection of these time-course plots indicates several distinct fixation patterns. One of the most evident effects in both groups is a robust acceleration of (anticipatory) fixations to the Target object that begins soon after the verb is spoken. Interestingly, the timing at which fixations to the Target object diverges from fixations to other items appears similar between groups. Additionally, looks to the Agent-Related object increase soon after the agent is named in both groups. However, fixations to the Action-Related object differ by group: The SLI group did not show an increase in fixation

proportion to the Action-Related distractor that begins after the action is spoken, whereas the TD group did show an increase. We discuss these patterns in greater detail below.

3.4 Time-course of target fixations

At first glance, anticipatory looks to the Target are evident, starting from the latter half of the action, with Target fixations increasing through the rest of the sentence. We measured potential differences in the time-point at which these looks to the target diverged from other images by conducting point-by-point *t*-tests at each 10 ms bin. We compared the mean fixation proportions to the Target object and fixations to the Agent-Related item, which was the second most highly fixated image in each group. To minimize the potential that reported differences, as measured by these multiple *t*-tests comparisons, might have arisen spuriously, we report only the earliest moment where a minimum of five subsequent, consecutive *t*-test values indicate a significant difference at alpha level of $p < .05$. These analyses showed that the target divergence time was similar between SLI and TD groups: 1340 ms for SLI and 1380 ms for TD. When we calculated a target divergence time, using the same procedure for each participant separately, there were no differences between the two groups $t(24) = -1.033, p = .31, d = 0.42$.

Although there were no group differences in this point-by-point timing measure, similar time-course averages could result from a number of potential differences in looking behavior and processing. For example, one group might have been faster at initially gazing at the Target, but then quickly shifted to other images, whereas the other might first have directed their looks at a slower latency but for a longer duration. Alternatively, the number of fixations might vary between groups, as observed between children with and without reading comprehension deficits (Nation, Marshall, & Altmann, 2003). We examined each of these possibilities in the next set of analyses, which are presented in Table 2.

3.4.1 Timing of initial looks—One possibility is that timing differences between groups might arise from differences in the speed at which looks were initially directed to the Target object. To explore this possibility, we measured the latency of initial saccades that landed on the Target object, post-action onset to sentence offset. The results indicated that there was no difference in the latency of the initial saccades for the SLI and age-matched controls, $t(24) = 1.17, p = .25, d = 0.47$.

3.4.2 Duration of looking—Next, we determined whether group differences might have existed in the average amount of time spent gazing at the Target per fixation. This was measured by calculating the total time spent fixating on the Target in the period from action onset to sentence offset and then dividing this by the total number of fixations generated to the Target object in this period. The results showed that the two groups were not significantly different in the amount of time that they spent gazing at the Target, $t(24) = -.725, p = .48, d = 0.29$.

3.4.3 Number of fixations—We then determined whether the total number of fixations to the Target object varied between groups by measuring the overall number of fixations to the

Target from action onset to target offset. Again, there was not a significant difference between the two groups, $t(24) = .417, p = .68, d = 0.17$.

3.4.4 Anticipatory fixations—The above analyses concerned group differences in looking behaviors across time-windows that precede and follow the onset of the target word, i.e., using eye-movement measures that are not solely anticipatory. In this section, we discuss group differences in solely anticipatory fixations. Anticipatory looking was computed as the mean proportion of time spent fixating on the Target object from action onset to target onset, i.e., over the portion of the sentence during which the necessary information to generate anticipatory looks was available. Because we are interested only in fixations that could have been plausibly generated in response to the action, fixations were excluded from the analysis if their preceding saccade was initiated prior to action onset.

Using these measurements, we determined whether participants' fixations to the Target region significantly differed from fixations to other regions during the same period. We conducted several planned comparisons to compare fixations between the Target region and the (1) Agent-Related item, (2) Action-Related item, and (3) Unrelated item. If eye movements were driven by combinatorial integration of meanings from both the sentential agent and action, then we should expect to see differences between the Target and all three other regions separately, for SLI and TD groups. This is, in fact, what we found, as presented in Table 3.

Next, using a separate planned comparison, we determined whether the proportion of anticipatory fixations to the target differed between groups. The comparison revealed no significant group differences, $t(24) = .331, p = .74, d = 0.14$.

3.4.5 Time-course of fixations to the Action-Related item—One interesting pattern that was apparent from visual inspection of the time-course of fixations was that the participants with SLI did not generate additional looks to the Action-Related item after hearing the action, whereas the TD participants did. To quantify when these post-verbal fixations diverged from that of looks to the Unrelated items, we conducted point-by-point t -tests to compare between-mean fixation proportions to the Action-Related item and that of the Unrelated object, from action onset to sentence offset. As above, only time-windows at which a minimum of five consecutive time points reached significance on this t -test measure are reported. Within this time-window, the SLI group did not significantly differ in their fixations to the Action-Related or Unrelated items, while the TD group's fixations to the Action-Related and Unrelated differed continuously in a time-window ranging from 1510 to 1890 ms post-sentence onset (i.e., 608 to 988 ms post-action onset). Further statistical analysis within this time window (1510–1890 ms) indicated that a children with SLI looked less towards the Action-Related item in this window than the TD group, $t(24)=2.12, p<.04, d=0.86$. Fixations between Action-Related and Unrelated items did not significantly differ for the adolescents with SLI, $t(11)=.53, p = .60, d = 0.32$, while the TD adolescents did look more to the Action-Related vs. Unrelated in this period, $t(13)=3.30, p = 0.006, d = 1.83$.

The prior analysis suggests that, as a group, adolescents with SLI do not show a post-verbal increase in fixation towards the action-related item, unlike the TD group. We were interested

in determining whether the absence or presence of the action-related effect was stable across individual group members. We approached this question in two ways: 1) by carrying out point-by-point t-test analyses for each participant and 2) by comparing average fixation proportion to the action-related and unrelated items over larger-time windows for each participant.

For the first approach, we compared the difference in each participant's fixations between the Action-Related and Unrelated item in each 10 ms bin post action onset. A participant was classified as exhibiting an "action effect" if they showed a significant difference for at least five consecutive bins. According to this relatively conservative criteria, 1 out of 12 adolescents with SLI exhibited an action effect, as did 7 out of 14 TD participants. Logistic regression analyses indicated that participants in the TD group were 11 times more likely to exhibit this effect than the adolescents with SLI, Odds ratio = 11, $p = .0016$, confidence interval, 1.50–229.8.

Secondly, we sought to determine to what extent individuals in each group might exhibit an action effect when collapsing across a relatively larger time window of analysis. We defined this time window of analysis to the period of time when group action effects were largest in our data (between 1510–1890 ms post action onset). We asked if each individual participant showed a significant positive difference in mean fixation between the Action-Related vs. Unrelated distractor. One out of 12 adolescents with SLI showed such a difference, and 9 out of 14 TD participants did¹. Logistic regression analysis indicated that TD adolescents were 19.8 times as likely to look more towards the Action-Related vs. Unrelated item in this time window, Odds ratio = 19.8, $p = .002$, confidence interval, 2.68–420.4.

3.4.6 Fixation distribution maps—The above data concern fine-grained timing differences in gaze to four large areas of interest of 400 x 400 pixels each. These areas are large enough that they have the potential to wash out differences in eye-movement behavior that may occur on a finer spatial scale within predefined areas of interest. Further, although we were interested primarily in time-course measures, we were curious whether there also were more global differences between TD and SLI groups in what we might call "style of gaze." Such differences might reflect, for example, a propensity to fixate on more central or more peripheral areas of the display or a more focal or diffuse pattern of gazes. To our knowledge, no such analysis has, to date, been carried out between SLI and TD groups.

To examine potential spatial differences in eye movements that were both language-mediated and linguistically unaffected, we calculated fixation distribution maps for each group using *iMap* software (Caldara & Miellet, 2011). Maps were generated by summing the coordinates of mean fixation durations for each participant across the relevant time-window and then normalizing these durations to *z*-scores. These data were smoothed with a 20-pixel (approximately 1-degree visual angle) filter. Statistical significance was calculated, using a robust multiple correction Pixel test (Chauvin, et al., 2005), an approach that has been validated largely in fMRI analysis but is increasingly being applied to eye-movement

¹Three of these nine participants in the TD group showed a marginal effect on this measure, with all $ps < .068$. No participants with SLI showed marginal effects.

data. Areas of dark red in the first two columns of Figure 3 indicate regions that were significantly fixated ($Z_{\text{crit}} > |3.89|$; $p < .05$) by each group (SLI and TD) in eye movements over several sentential time windows: (a) the image-preview period before sentence onset; (b) across the entirety of the spoken sentence; (c) as the Target word was spoken; and (d) during the “anticipatory” window, when the Action and subsequent article were heard. Areas of significant differences between the groups ($Z_{\text{crit}} > |4.06|$; $p < .05$) are also shown in the difference maps in the third column of Figure 3. Here, areas of dark red indicate regions where the SLI group fixated significantly more than did the TD group, whereas dark blue regions signify the opposite pattern. In general, these maps indicate that the SLI group fixated significantly less than did their TD peers on the central regions of the scene and on each individual object (indicated in dark blue in the subtraction image) as well as spent relatively more time fixating on the outer regions of the pictures (indicated in dark red in the subtraction image).

4. Discussion

The goal of this study was to examine lexical processing across simple sentences in adolescents with a history SLI versus their TD age-matched peers, using a design that required the coordination of lexical meaning across both an agent and an action. We used sentence stimuli that could be understood by preschool-age children, as determined by previous norming (Borovsky et. al., 2012), combined with a method that simply required participants to listen to sentences while viewing a picture. Although behavioral responses were requested to ensure that participants were attending to the task, these responses were not informative in regard to processing differences in this task; all participants achieved 100% accuracy. In contrast to these offline behavioral responses, our online measures of eye-gaze revealed important differences.

We assessed linguistically-mediated looking in two ways: first, with fine-grained time-course measures that collapsed across large spatial regions, and, second, with spatial maps of fixations that collapsed across large time-regions. Together, these measures allowed us to characterize group performance in the location and timing of linguistically-mediated gaze fixations during sentence comprehension.

For the time-course measures, we noted several group similarities and differences. First, adolescents with a history of SLI were no slower than were their age-matched peers in their visual fixations to the target object. Both groups were able to rapidly activate and integrate information across multiple lexical items to predict the likely sentence-final target item. Each group was equally fast to fixate on (anticipate) the target item, and they launched an equivalent number of fixations and spent an equivalent amount of time looking at the target object before and after it was spoken. This finding indicates that adolescents with SLI were just as fast as their TD peers to integrate information from the sentential agent and action to predict the likely sentential object. This pattern is not consistent with an account that individuals with SLI may have deficits in verb activation (Andreu, et al., 2012) or have slower speed of processing (Kail, 1994). However, because the items in this task are relatively simple, it is possible that the inclusion of more complex vocabulary and/or morpho-syntactic constructions may yield slowing in lexical activation. Alternatively,

additional context in longer sentences may facilitate lexical activation in individuals with SLI (e.g. (Montgomery, 2000) Future work would be necessary to distinguish between these accounts, and to determine what aspects of sentences may facilitate or hinder lexical activation.

Key differences were found in looks to the non-target items. After the verb was spoken, the TD group showed additional fixations to the Action-Related item. The adolescents with SLI, in contrast, did not gaze to the Action-Related distractor any more than they directed their gaze to the Unrelated distractor. This pattern of additional looking to the Action-Related item by the TD group is consistent with eye-tracking patterns observed for college-aged adults and TD children as young as age 3 (Borovsky et al., 2012).

One interpretation of these additional Action-Related fixations by unimpaired individuals is that they are continuing to activate items that may be locally consistent but globally implausible with the sentence-level message (Borovsky, et al., 2012; Kukona, et al., 2011; Tabor, et al., 2004). At first glance, this type of comprehension strategy may seem less efficient than simply narrowing one's expectations to items that are consistent only with a global sentential message. Such a strategy, however, may allow listeners to recover in noisy listening conditions when earlier items are not heard or when speakers convey unexpected information. In a sense, it may be helpful to "hedge one's bets" when interpreting language, considering the general unpredictability of language and speakers. It appears that typical adult and child listeners use this type of strategy to interpret and acquire language, whereas adolescents with SLI do not use this type of comprehension strategy with the type of simple sentences employed in our study.

Why might adolescents with SLI not entertain locally coherent action-related options in these tasks? One possibility, consistent with a processing deficit account of sentence interpretation in SLI (e.g., Montgomery & Evans, 2009), is that reduced processing capacity or cognitive resources limit the ability of individuals with SLI to entertain multiple sentence continuations in parallel. As a result, they engage in a compensatory processing strategy that relies on the interpretation of global contextual cues, which allows them to consider event-probable items as quickly as do their TD peers. This behavior is consistent with prior findings in the offline sentence comprehension literature that children with SLI engage in developmentally immature sentence strategies that lead them to rely on event-probable interpretations (Evans & MacWhinney, 1999; van der Lely & Dewart, 1986), and the reliance on this type of comprehension strategy increases as processing demands increase (Evans, 2002). A second explanation, consistent with a degraded lexical representation account of SLI, suggests that participants with SLI should activate fewer potential lexical continuations as the sentence unfolds. Concretely, this account would predict that adolescents with SLI should have little issue fixating towards highly expected items relative to TD peers, but that group differences should appear in anticipation of more weakly expected items, such as the Action-Related item in our task. We observed precisely this pattern in our study. This is analogous to findings of weak activation of lexically associated items in semantic priming paradigms in SLI (Lahey & Edwards, 1999; Mainela-Arnold, et al., 2010; Mainela-Arnold, et al., 2010; McGregor, 1997; Sheng & McGregor, 2010). Both

of these accounts raise an intriguing possibility that adolescents with SLI may show exaggerated difficulties in the online interpretation of unexpected sentential outcomes.

We also found striking group differences in the spatial gaze map analyses, which were exploratory analyses for which we did not have a priori hypotheses. Overall, the adolescents with SLI exhibited more diffuse patterns of fixations to the scene images and spent less time gazing to the center of the images than their TD peers. Instead, adolescents with SLI were more likely to fixate toward the edges of images. Importantly, this pattern existed whether or not the fixations were accompanied by language, which leads to the possibility that individuals with SLI may have poorer control of visual fixations across the experimental images. Another possible interpretation is that the concomitant motor impairments reported for children with early language delays and language impairments (Chuang, et al., 2011; Hill, 1998, 2001; Rechetnikov & Maitra, 2009; Webster, et al., 2005) also may manifest in the visual domain, as with gaze control.

Alternatively, while gaze is used as a means of linking and monitoring information in the external environment, studies show that as processing demands increase during cognitive tasks, there is a corresponding decrease in individuals' visual engagement with the environment (Glenberg, et al., 1998), such as when adult drivers look away from the central point of the scene (e.g., the road) when cell phone conversations become attentionally demanding (Strayer, et al., 2003). Thus, one possible interpretation of the differences in gaze patterns for the SLI and TD groups is that the differences in the fixation patterns reflect differences in the two groups' processing capacity. However, it should be noted that children with SLI do not appear to have deficits in visuospatial short-term memory relative to TD peers (e.g. Archibald & Gathercole, 2006; Henry, et al., 2012; but cf. Hick et. al. 2005). Alternatively, the spatial gaze differences for the SLI group may signify poorly specified lexical-semantic representations (Lahey & Edwards, 1999; Mainela-Arnold, Evans, & Coady, 2010b; McGregor, 1997; Sheng & McGregor, 2010). In particular, it is possible that the wider distribution of fixations seen for the SLI group reflects reduced efficiency in processing and interpreting the relevant semantic and perceptual features of the visual stimuli.

It is important to note, however, that the findings from the spatial gaze map analysis are based on a relatively novel approach to examining simultaneous auditory and visual lexical processing in adolescents with SLI and are, therefore, only preliminary. It should be emphasized that our interpretations are post hoc because our experiment was not designed to test spatial differences in eye gaze. Importantly, while these spatial effects are intriguing, and warrant further investigation, it is unlikely that they alter the time-course analyses, as we included all fixations that occurred over an entire region of interest. The fact that we observed similar *timing* in fixations to the Target for both groups further suggests that the spatial differences did not alter our main findings.

In this study, we used the unique advantages afforded by eye-tracking measures to determine that adolescents with SLI predict the likely ending of simple transitive sentences with expected endings as rapidly as do their age-matched peers. Despite this similarity, there were key differences in online performance of this task for the two groups. Most noticeably,

individuals with SLI showed differences in the pattern of fixations to non-target items and in the spatial distribution of their fixations around the visual scene. Adolescents with SLI appear to consider fewer lexical candidates than TD peers as the sentence unfolds, and instead restrict their fixations to highly likely sentence outcomes. These findings indicate that there are important, albeit subtle, differences in the manner in which individuals with SLI and TD peers activate lexical information in even simple sentences. Future research needs to address domain general processing speed and capacity accounts of SLI that may become particularly relevant in more extended sentence contexts. Additional work should examine the extent to which deficits in sentence comprehension in SLI are secondary to deficits in degraded lexical activation or poorly specified lexical-semantic representations or, instead, a reflection of an (adaptive) over-reliance on potentially non-linguistic event knowledge.

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Appendix A

The 32 Sentences used in the Study

The fireman rides the truck.
The girl rides the bike.
The fireman tastes the hamburger.
The girl tastes the candy.
The shark swims in the ocean.
The boy swims in the pool.

The shark catches the fish.
The boy catches the ball.
The pirate hides the treasure.
The dog hides the bones.
The pirate chases the ship.
The dog chases the cat.
The baby drinks the milk.
The woman drinks the water.
The baby wears the diaper.
The woman wears the dress.
The cat catches the bird.
The frog catches the fly.
The cat jumps into the couch.
The frog jumps into the pond.
The monkey jumps through the trees.
The dolphin jumps through the waves.
The monkey eats the banana.
The dolphin eats the fish.
The baby eats the cookie.
The cow eats the grass.
The baby sleeps in the crib.
The cow sleeps in the barn.
The boy flies the kite.
The pilot flies the airplane.
The boy wears the t-shirt.
The pilot wears the helmet.

CEU questions (correct answers marked in bold)

1. Which is NOT a benefit of eyetracking for studying language-disordered populations?
 - a. Does not require a motor response.
 - b. Can measure language comprehension in real-time.
 - c. **Measures brain activity in response to language.**
 - d. Simply requires a participant to gaze at an image while listening to language.
2. Children with SLI are just as fast as age-matched peers to predict the final word of simple sentences (T/F) (**True**)
3. Children with SLI showed spatial but not timing differences in their eye-gaze patterns. (T/F) (**False**)
4. Which description below best summarizes the timing of fixations across the sentences?

- a. Children with SLI showed an identical pattern of fixations compared to the age-matched group.
 - b. **Children with SLI showed a different pattern of activation to Action-Related items compared to the age-matched group.**
 - c. Children with SLI were slower than the control group, but were otherwise identical in the pattern of fixations to all items.
 - d. Children with SLI showed a different pattern of activation to Agent-Related items compared to the age-matched group.
5. Which theory of SLI do the findings of this study fail to support?
- a. **Children with SLI show slower speed of lexical processing.**
 - b. Children with SLI use immature interpretation strategies.
 - c. Children with SLI have degraded semantic representation.
 - d. Children with SLI have reduced processing capacity.

Spoken Sentence					Target	Agent-Related	Action-Related	Unrelated
The	pirate	hides	the	treasure	Treasure	Ship	Bones	Cat
The	pirate	chases	the	ship	Ship	Treasure	Cat	Bones
The	dog	hides	the	bones	Bones	Cat	Treasure	Ship
The	dog	chases	the	cat	Cat	Bones	Ship	Treasure
Art 1	Agent	Action	Art 2	Target				

Figure 1. An example of an image array and associated auditory stimuli used in the study. In any single trial, one of four possible auditory sentences is paired with the image display. Across all possible image/sentence combinations, each individual image appears in all possible conditions, yielding a completely balanced design.

Figure 2.
Time-course of fixating on target and competitor interest areas during the sentence for participants with SLI (A) and for TD controls (B).

Figure 3.

Group and differential fixation maps across several time windows. Areas of dark red in the subtraction image indicate regions where the SLI group fixated significantly more than did the TD group, and areas of dark blue indicate areas where the TD group spent more time in fixation.

Table 1

Standardized measures for adolescents with Specific Language Impairment (SLI) and age-matched, typically-developing controls (TD) for tests completed at the Child Language and Cognitive Processes Lab.

	SLI			TD		
	Mean	SD	Range	Mean	SD	Range
Age in months	198.00	26.38	157–241	193.93	22.57	157–246
Leiter-R: Nonverbal IQ ^a	106.41	14.09	82–127	113.21	9.09	100–127
CELF-4 ^b Formulated Sentences	7.20	3.40	2–11	13.20	1.12	10–15
CELF-4 ^b Recalling Sentences	3.00	2.00	1–6	11.80	1.17	8–14
CASL ^c Nonliteral Language	74.90	10.47	52–92	102.80	9.50	81–118
CASL ^c Meaning from Context	76.60	12.50	60–93	110.70	13.40	88–129
CREVT ^d Expressive	84.00	8.90	73–102	105.10	8.74	90–115
CREVT ^d Receptive	85.50	11.50	66–101	107.10	10.54	80–118

^aLeiter-R (International Performance Scale-Revised, Roid & Miller, 1997), standard scores ($M = 100$, $SD = 15$).

^bClinical Evaluation of Language Fundamentals-4 (CELF-4; Semel et al., 2003), subtest standard scores ($M = 10$, $SD = 3$).

^cComprehensive Assessment of Spoken Language (CASL; Carrow-Woolfolk, 1999), subtest standard scores ($M = 100$, $SD = 15$).

^dComprehensive Receptive Expressive Vocabulary Test-2 (CREVT-2; Wallace & Hammill, 2002), standard scores ($M = 100$, $SD = 15$).

Table 2

Fixation measures of mean latency, mean duration, and mean number of fixations to Target object from action onset to sentence offset.

Group	Mean latency of initial saccade (in ms post-action onset):	Mean fixation duration (in ms)	Mean number of fixations
SLI	721 (35.2)	336.4 (22.6)	1.99 (0.12)
TD	746 (32.6)	358.7 (20.9)	1.92 (0.12)

Note. Standard error reported in parentheses.

Table 3

T-scores for comparisons of fixations in the anticipatory time-window to the Target vs. Distractors.

Group	Target- vs. Agent- Related	Target- vs. Action- Related	Target vs. Unrelated
SLI	2.130*	3.528**	4.899***
TD	2.774*	3.918**	5.126***

Note.

*
 $p < .04$,

**
 $p < .01$,

 $p = .00$