Research Note

Sensitivity to Audiovisual Temporal Asynchrony in Children With a History of Specific Language Impairment and Their Peers With Typical Development: A Replication and Follow-Up Study

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Purpose: Earlier, my colleagues and I showed that children with a history of specific language impairment (H-SLI) are significantly less able to detect audiovisual asynchrony compared with children with typical development (TD; Kaganovich & Schumaker, 2014). Here, I first replicate this finding in a new group of children with H-SLI and TD and then examine a relationship among audiovisual function, attention skills, and language in a combined pool of children.

Method: The stimuli were a pure tone and an explosion-shaped figure. Stimulus onset asynchrony (SOA) varied from 0–500 ms. Children pressed 1 button for perceived synchrony and another for asynchrony. I measured the number of synchronous perceptions at each SOA and

calculated children's temporal binding windows. I, then, conducted multiple regressions to determine if audiovisual processing and attention can predict language skills.

Results: As in the earlier study, children with H-SLI perceived asynchrony significantly less frequently than children with TD at SOAs of 400–500 ms. Their temporal binding windows were also larger. Temporal precision and attention predicted 23%–37% of children's language ability.

Conclusions: Audiovisual temporal processing is impaired in children with H-SLI. The degree of this impairment is a predictor of language skills. Once understood, the mechanisms underlying this deficit may become a new focus for language remediation.

Most of our daily experiences are multisensory in nature. For example, we not only hear a person talk but also see him/her articulate speech sounds. We not only see a baseball hit the glove but also feel its impact, and so on. Sensations from different senses blend seamlessly together, providing us with rich sensory environments and imparting significant benefits in a range of cognitive tasks, from simple stimulus detection (e.g., Schröger & Widmann, 1998) to speech-in-noise perception (e.g., Barutchu et al., 2010; Sumby & Pollack, 1954). Many factors determine whether or not different senses

are integrated into a coherent percept (Stein & Meredith, 1993). These include temporal and spatial proximity, semantic congruency, and the effectiveness of individual senses in conveying information. In this research article, I focus on just one of these factors, namely temporal proximity, which refers to stimuli in different modalities being more likely to be perceived as belonging to the same event if they occur close to each other in time. This principle applies to various combinations of senses; however, in this study, I discuss it in the context of audiovisual processing.

On the basis of earlier investigations, we know that auditory and visual stimuli do not have to be truly synchronous to be perceived as such. Instead, even onset-to-onset separations of several hundred milliseconds may lead to the perception of synchrony, depending on the nature of the stimuli (e.g., complex vs. simple; Vatakis & Spence, 2010; Vroomen & Stekelenburg, 2011), the order of the two modalities (Bushara, Grafman, & Hallett, 2001; Grant, van Wassenhove, & Poeppel, 2004; Lewkowicz, 1996; van Wassenhove, Grant, & Poeppel, 2007), and the perceiver's

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previous experience (e.g., Petrini et al., 2009). This temporal window of separation that nonetheless leads to the perception of synchrony is often referred as the *temporal binding window* (TBW; for a review, see Keetels & Vroomen, 2012). Previous studies showed that smaller TBW is associated with better perception of degraded audiovisual speech (Conrey & Pisoni, 2006) and greater susceptibility to the McGurk illusion (Stevenson, Zemtsov, & Wallace, 2012). In other words, smaller TBW is a sign of more effective audiovisual integration processes.

TBW has a protracted developmental course. It is very broad in infants (Lewkowicz, 1996, 2010), reduces slowly in size during the school years, and reaches adult size only by late adolescence (Hillock, Powers, & Wallace, 2011; Hillock-Dunn & Wallace, 2012; Kaganovich & Schumaker, 2014; Lewkowicz & Flom, 2014). Note that its developmental trajectory appears to be altered in a number of neurodevelopmental disorders (for a review, see Wallace & Stevenson, 2014), such as autism (e.g., Donohue, Darling, & Mitroff, 2012; Foss-Feig et al., 2010; Kwakye, Foss-Feig, Cascio, Stone, & Wallace, 2011; Stevenson et al., 2014), dyslexia (Hairston, Burdette, Flowers, Wood, & Wallace, 2005), and specific language impairment (SLI; e.g., Grondin et al., 2007; Kaganovich, Schumaker, Leonard, Gustafson, & Macias, 2014), suggesting that a dysregulation in the audiovisual temporal function may play a role in some of the deficits associated with these disorders.

In an earlier study (Kaganovich et al., 2014), we compared the ability of school-age children with a history of SLI (H-SLI) and of children with typical development (TD) to detect audiovisual temporal asynchrony in a simultaneity judgment task (SJT). We used simple and relatively long stimuli (namely, a 200-ms pure tone and an explosion-shaped red figure), which posed no sensory or cognitive processing challenges. We varied the stimulus onset asynchrony (SOA) from 0–500 ms in 100-ms increments and recorded the number of synchronous perceptions at each SOA, with the expectation that as the SOA increased, the number of synchronous perceptions would decrease. Children with H-SLI were significantly more likely than their peers with TD to perceive the two stimuli as synchronous at the longest SOAs of 400 and 500 ms, indicating atypical audiovisual temporal function in this group. Those children, crucially, who were more accurate asynchrony detectors also had better language skills as measured by the Core Language Score of the Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4; Semel, Wiig, & Secord, 2003).

The relationship between audiovisual temporal function and language ability reported in our 2014 study was striking, with up to 36% of variability in children's language aptitude being accounted for by their performance on the SJT. However, our study also had several limitations, which prevented us from making strong conclusions. The main limitation was a relatively small number of participants ($n = 15$) in each group. In addition, the risk of developing attention-deficit/hyperactivity disorder (ADHD) as measured by the ADHD Index of the Conners' Rating

Scales–Revised (Conners, 1997) was a strong predictor for performance on the SJT. However, due to the complexity of other analyses in the previous study, including those related to electrophysiological measures, a more direct relationship among attention skills, performance on the SJT task, and language ability was not examined. Also, we measured sensitivity to audiovisual asynchrony in children at individual SOAs, which was motivated by the need to have a direct correspondence between behavioral and electrophysiological measures. As a result, we did not calculate children's TBW, which would allow for an easier comparison of our results with the studies of audiovisual temporal processing in other populations.

The goal of this follow-up study is to address the above limitations. I do so by first replicating our earlier findings in a new group of children with H-SLI and TD. Second, in addition to measuring asynchrony perception at each SOA, I also calculated the size of the TBW in each group. Also, I conducted multiple regression analyses on the data pooled from both studies to determine to what extent audiovisual temporal function and attention skills predicted children's linguistic ability.

Our focus on school-age children with H-SLI is intentional. Most children are diagnosed with this disorder during the preschool years, at which time their language impairment is easily detectable not only through clear symptoms of difficulty in their everyday language use but also with available standardized tests. By the time these children reach school age, they may be able to pass standardized language assessments. Yet, this alone does not signify recovery. Relatively few of the existing tests have sufficient sensitivity and specificity for detecting language difficulties in older children (Spaulding, Plante, & Farinella, 2006). Furthermore, within the public school system, the choice of tests used for diagnostic purposes may be motivated by factors unrelated to these tests' efficacy. For example, one recent study found that the year of publication was the only predictor of a screening language test selection in a school setting (Betz, Eickhoff, & Sullivan, 2013). A number of studies that did use age-appropriate language tests, which sufficiently challenged different aspects of language knowledge in school-age children, showed that even those children who were labeled as *recovered from SLI* on the basis of standardized tests continued to show deficits in sentence repetition (Conti-Ramsden, Botting, & Faragher, 2001), nonword repetition (Bishop, North, & Donlan, 1996; Stothard, Snowling, Bishop, Chipchase, & Kaplan, 1998), and comprehension of nonliteral language (Nippold & Fey, 1983). Furthermore, even when children with H-SLI do score within the normal range on standardized assessments, their scores still tend to be significantly lower compared with their peers with TD (Kaganovich et al., 2014; Kaganovich, Schumaker, & Rowland, 2016).

Relatively weak language skills can have a significant negative impact on children's academic performance. In fact, research on the academic and social outcomes in school-age children who were diagnosed with SLI during preschool is unequivocal: without continued intervention,

these children's prognosis for social and academic success remains poor (Nippold & Schwarz, 2002). For example, the 10-year Iowa-based longitudinal study, which focused on changes in individual language skills over the school years (Tomblin & Nippold, 2014), showed that children who were diagnosed with SLI during the preschool years were significantly more likely to repeat a grade than their peers with TD. Furthermore, although the percentage of children with TD repeating a grade remained constant for the second, fourth, and eighth grades (approximately 4%), it steadily increased for children with H-SLI, reaching 15% by the eighth grade. Those children who had low composite language scores during kindergarten also were described by their teachers as performing worse academically in the fourth grade. This relationship was linear, meaning that even children with slightly reduced language ability did more poorly academically than those children whose language skills were average or above average. Note that over 25% of 10th graders who had a diagnosis of SLI during the preschool years failed to reach reading competence, defined as reading at the fifth-grade level. In sum, we see not only that children with H-SLI do worse than their peers with TD, but also, and importantly, that their differences from peers with TD tend to increase during the school years.

The school environment, with its high background noise and numerous distractions, is exactly the environment in which strong audiovisual integration skills can enable successful learning. We know that audiovisual integration facilitates some of the same linguistic skills that are known to be impaired in SLI, such as phonological processing (Hollich, Newman, & Jusczyk, 2005; Teinonen, Aslin, Alku, & Csibra, 2008), lexical processing (Jesse & Johnson, 2016), and speech-in-noise perception (Barutchu et al., 2010). In addition, we know that the maturation of the audiovisual function does not end until late adolescence (Hillock et al., 2011; Hillock-Dunn & Wallace, 2012; Kaganovich, 2016), potentially giving speech-language pathologists a long window of opportunity to improve children's language outcomes. Therefore, understanding the status of audiovisual skills in school-age children with H-SLI has strong potential to influence language and academic outcomes in this population.

Method

Participants

Participants of the 2014 study were described in detail in our previous publication (Kaganovich et al., 2014). They consisted of 15 children with H-SLI (three girls, 12 boys, $M = 9;0$ [years;months], age range 7;3–11;0) and 15 age-matched children with TD (four girls, 11 boys, $M = 9;1$, age range 7;4–10;10). For the replication portion of this study, I recruited a new group of children with H-SLI ($n = 19$, four girls, 15 boys, $M = 10;2$, age range 7;7–13;8) and a new age-matched group of children with TD ($n = 19$, seven girls, 12 boys, $M = 10;4$, age range 7;10–13;7). All participants were monolingual native speakers of American English. All

gave their written assent to participate in the experiment. In addition, at least one parent of each child gave a written consent to enroll their child in the study. The study was approved by the Institutional Review Board of Purdue University, and all study procedures conformed to the Code of Ethics of the World Medical Association (1964).

The new cohort of children with H-SLI was similar to the 2014 group in that they were diagnosed with SLI when they were 4 or 5 years of age and tested in the current study at 7–13 years of age. Their diagnosis was based on either the Structured Photographic Expressive Language Test–Second Edition (Werner & Kresheck, 1983) or the Structured Photographic Expressive Language Test–Preschool 2 (Dawson, Eyer, & Fonkalsrud, 2005). One more child with H-SLI was diagnosed on the basis of the Clinical Evaluation of Language Fundamentals Preschool–Second Edition (Semel, Wiig, & Secord, 2004). All tests have shown good sensitivity and specificity (Greenslade, Plante, & Vance, 2009; Plante & Vance, 1994). At the time of the current study, these 38 new children (19 with H-SLI and 19 with TD) were administered the same battery of screening tests as the 30 children from the 2014 study, except for the Test of Everyday Attention for Children (Manly, Robertson, Anderson, & Nimmo-Smith, 1999), which did not relate to any of the children's cognitive skills in the earlier study. This battery included the following tests. To assess children's language skills, we administered the four subtests of the Clinical Evaluation of Language Fundamentals–Fourth Edition (CELF-4; Semel et al., 2003) that together comprised the Core Language Score (CLS): the Concepts and Following Directions (7- to 12-year-olds only), Recalling Sentences, Formulated Sentences, Word Structure (7- and 8-year-olds only), Word Classes-2 Total (9- to 12-year-olds only), and Word Definitions (13-year-olds only). Because working verbal memory often continues to be an area of weakness in school-age children with H-SLI, we evaluated it with the number memory forward and number memory reversed subtests of the Test of Auditory Processing Skills (Martin & Brownell, 2005) and the nonword repetition task (Dollaghan & Campbell, 1998). Parents of all children filled out a Parent Rating Scale of the Conners' Rating Scales–Revised (Conners, 1997). The ADHD Index derived from this questionnaire reflects children's overall risk for developing ADHD. In all participants, handedness was assessed with an augmented version of the Edinburgh Handedness Questionnaire (Cohen, 2008; Oldfield, 1971). The level of mothers' and fathers' education was measured as an indicator of children's socioeconomic status. All participants were free of neurological disorders (e.g., seizures), passed a hearing screening at a level of 20 dB HL at 500, 1000, 2000, 3000, and 4000 Hz, and were reported to have normal or corrected-to-normal vision. None had developmental delays defined as an index score one standard deviation or more below the mean on the the Test of Nonverbal Intelligence–Fourth Edition (Brown, Sherbenou, & Johnsen, 2010). The distribution of index scores for the Test of Nonverbal Intelligence–Fourth Edition has a mean of 100 and an *SD* of 15. No child exhibited symptoms of autism on the basis of the

Childhood Autism Rating Scale–Second Edition (Schopler, Van Bourgondien, Wellman, & Love, 2010). Three children in the H-SLI group and two children in the TD group were left handed. All the others were right handed.

Eight children with H-SLI had a diagnosis of ADHD, with four taking medications to control symptoms. One more child with H-SLI had a diagnosis of dyslexia. Both ADHD and dyslexia are comorbid with SLI (Flax et al., 2003; Mueller & Tomblin, 2012). I did not exclude children with these disorders because this comorbidity reflects a realistic combination of deficits typically present in a group of older children with H-SLI. In addition, linguistic deficits associated with ADHD tend to differ from those associated with SLI (Redmond, 2005; Redmond, Thompson, & Goldstein, 2011). Children with TD did not have a history of SLI or any other language-related developmental delays. None had a diagnosis of ADHD or dyslexia.

Procedure

Children performed a SJT, which was identical to the one described in several earlier publications from our laboratory (Kaganovich, 2016; Kaganovich et al., 2014; Kaganovich & Schumaker, 2016). The stimuli were a 2-Hz tone and an explosion-shaped red figure, both 200 ms in duration. They were presented at six SOAs, 0 (synchronous presentation), 100, 200, 300, 400, and 500 ms, with the sound preceding the figure in half of trials (auditory-visual [AV]) and with the figure preceding the sound in another half (visual-auditory [VA]). In addition, on some trials, only the sound (auditory [A]) or only the figure (visual [V]) was present. In the original 2014 study, we used these catch trials to evaluate brain responses elicited by each modality. Although these trials were not necessary for the goals of the current experiment, I included them to keep the paradigm identical to the 2014 task. Five instances of each of 13 different trials (five AV SOAs, five VA SOAs, synchrony, A, and V) occurred randomly within each block to minimize the possibility of sensory recalibration (Navarra et al., 2005; Vatakis, Navarra, Soto-Faraco, & Spence, 2007; Vroomen, Keetels, de Gelder, & Bertelson, 2004). The experiment consisted of five blocks, which yielded 25 responses to each trial type. The task was presented as a game, in which a girl and a boy used futuristic weapons to scare away dragons. One weapon shot lights, and another weapon shot sounds. The two had to hit the dragon at the same time to scare it away. Children were told that the boy and the girl were still learning to use these weapons. They often made mistakes. As a result, sometimes the sound came first, sometimes the light came first, and sometimes either the boy or the girl forgot to shoot altogether. In the latter case, children would only see an explosion figure or only hear a sound. In short, these instructions guided children to press one button on the response pad if the sound and the explosion figure occurred simultaneously and another button for all other perceptions. The response window lasted for 2,200 ms and was followed by an inter-trial interval, varying randomly among 350, 700, 1,050, and

1,400 ms. Hand-to-response button mapping was counter-balanced across participants.

Data Analysis

Group differences on screening tests were analyzed with one-way analyses of variance (ANOVAs). The Levene statistic was used to check for the homogeneity of variances across groups. When variances differed, the Brown–Forsythe robust test of equality of means was used to determine significance.

Data analysis from the SJT proceeded in multiple steps. Our first goal was to replicate children’s performance on the SJT from the 2014 study. To that end, I recorded the number of synchronous perceptions at each SOA. In the 2014 experiment, the SJT was combined with electroencephalographic recordings, which required a significant number of trials (i.e., 50) with each SOA. In the current study, which contains only behavioral measures, the number of trials was cut in half. However, to make behavioral data from the 2014 cohort of children compatible with the data collected during the current study, I have reanalyzed the 2014 results so that all synchrony perception measures were based on children’s performance during the first five (out of 10) blocks, yielding 25 responses for each trial type, which is identical to the current study design. Note that the length of a block was the same in both studies.

Repeated measures ANOVAs were used to compare groups’ performance on the SJT, with six levels of SOA as a within-group measure. Earlier studies showed that VA asynchronies are typically harder to detect than AV asynchronies (Bushara et al., 2001; Dixon & Spitz, 1980; Grant et al., 2004; Lewkowicz, 1996). Therefore, separate analyses were conducted on AV and VA SOAs. In addition, to directly compare children’s performance in the 2014 and the current studies, I conducted repeated measures ANOVAs with the year of the study (2014 vs. 2016) as a between-groups variable and six SOAs as a within-group variable, separately for children with H-SLI and TD.

The second goal of the study was to measure and compare TBWs in children with H-SLI and TD. I used the glmfit function in MATLAB (MathWorks, Inc., Natick, MA) to fit two sigmoid functions to the number of synchronous perceptions, separately for the VA and AV SOAs, in each child. The width of the left (on the basis of VA SOAs) and the right (on the basis of AV SOAs) side of each function was then measured at 40% of its maximum.¹ Data from the 2014 and 2016 studies were combined for this analysis. Function curves could not be fitted to the data from five children with H-SLI and one child with TD. Their data

¹In studies with adults and older children, it is common to use a 50% or 75% of the maximum point for measuring TBWs. However, in younger children, and especially in children who show a deficit in audiovisual temporal processing, the function’s slopes are significantly more gradual than in adults, with group differences not becoming apparent until longer SOAs. This made the 40% of the maximum point a more appropriate measure of the TBW in our group of children.

were excluded from group comparisons and from regression analyses (see below) involving the TBW.

Also, I aimed to determine whether sensitivity to audiovisual temporal information and attention skills can predict language ability in children. To this end, I conducted multiple regression analyses, in which the CLS from CELF-4 was always entered as a dependent variable, while the ADHD Index from the Conners' Rating Scale and one of the following four measures of the audiovisual temporal function were entered as predictors: the size of AV TBW; the size of VA TBW; the average of synchronous perceptions over the two longest AV SOAs (i.e., 400 and 500 ms); and the average of synchronous perceptions of the two longest VA SOAs. The last two measures were identical to those used in our 2014 study and were included, in part, to fully replicate our earlier regression findings. In each of the four multiple

Table 1. Group comparison on age, nonverbal intelligence (TONI-4), socioeconomic status (parents' education), risk of developing ADHD (ADHD Index), linguistic ability (CELF-4), and verbal working memory (TAPS-3 and nonword repetition).

Test	H-SLI (n = 19)	TD (n = 19)	F	p
Age	10.2 (0.4)	10.3 (0.4)	<1	
TONI-4	106 (2.1)	109 (2.3)	<1	
Mother's education	15 (0.8)	15.5 (0.5)	<1	
Father's education	13.5 (0.6)	17.4 (0.8)	15.4	<.001
ADHD Index	56.5 (2.7)	47.4 (1.3)	9.3	.004
CELF-4				
C&FD	9.3 (0.6)	12 (0.4)	13.1	.001
RS	7.6 (0.6)	12.1 (0.5)	33.9	<.001
FS	9.6 (0.4)	12.6 (0.4)	25.8	<.001
WS	9.8 (1.3)	11.8 (0.5)	1.7	.238
WC-2				
R	11 (0.7)	13.4 (0.6)	6.8	.015
E	10.3 (0.7)	11.9 (0.5)	4.4	.046
T	10.6 (0.7)	12.8 (0.5)	6.7	.016
CLS	95.5 (2.5)	114.3 (2.1)	33.8	<.001
TAPS-3				
Numbers forward	7.2 (0.5)	10.7 (0.6)	21.7	<.001
Numbers reversed	8.6 (0.5)	11.6 (0.7)	12.8	.001
Nonword repetition				
One syllable	96.9 (1.3)	99.1 (0.6)	2.3	.136
Two syllable	94.7 (1)	97.9 (0.7)	7	.012
Three syllable	85.7 (2.6)	97.7 (0.7)	20.3	<.001
Four syllable	65.3 (3.4)	85.4 (2.2)	24	<.001
Average	81.2 (1.8)	93.3 (0.9)	34.9	<.001

Note. Numbers in parentheses are standard errors of the mean. Numbers for TONI-4 and CLS (from CELF-4) are standard scores with the mean of 100 and an SD of 15. Numbers for all the subtests of CELF, as well as for the two subtests of TAPS-3 are standard scores with the mean of 10 and an SD of 3. Numbers for the ADHD Index are standard scores with the mean of 50 and an SD of 10. Numbers for the nonword repetition task are the percentage correct of the repeated phonemes. TONI-4 = Test of Nonverbal Intelligence—Fourth Edition; ADHD = attention-deficit/hyperactivity disorder; CELF-4 = Clinical Evaluation of Language Fundamentals—Fourth Edition; TAPS-3 = Test of Auditory Processing Skills—Third Edition; H-SLI = history of specific language impairment; TD = typical development; C&FD = Concepts and Following Directions; RS = Recalling Sentences; FS = Formulated Sentences; WS = Word Structure; WC-2 = Word Classes-2; CLS = Core Language Score; R = receptive; E = expressive; T = total.

regressions, the forced entry method was used to create the model. Variance inflation factor (VIF) screened for multicollinearity. None of the VIF numbers exceeded 10, with the average VIF being close to 1 (Field, 2013), suggesting that multicollinearity was not a significant factor. In addition, the standardized DfBETA was used to screen for outliers. However, no cases with DfBETA over 1 were detected.

Results

Group Characteristics

The outcome of all screening tests is summarized in Table 1. The groups did not differ on age or nonverbal

Figure 1. Performance on the simultaneity judgment task: an across-groups comparison. Stimulus onset asynchronies (SOAs) at which children with TD were significantly more sensitive to audiovisual asynchrony than children with H-SLI are marked with asterisks (for specific *p* values, see Table 3). Error bars are standard errors of the mean. Note that lines connecting individual data points in each group do not reflect a fitted function and are included only for ease of viewing. TD = typical development; H-SLI = history of specific language impairment; VA = visual-auditory; AV = auditory-visual.

Table 2. Performance on the SJT: percentage of synchronous perceptions at individual SOAs in each group in the 2014 and the current (2016) studies.

Group	SOA (ms)										
	-500	-400	-300	-200	-100	0	100	200	300	400	500
H-SLI											
2014	38.9 (6.3)	47.7 (5.9)	63.5 (5.9)	78.4 (4.2)	81.6 (4.1)	81.3 (4.1)	77.6 (4.8)	72.3 (4.8)	60.3 (5.1)	40.3 (6.7)	33.3 (6.7)
2016	32.2 (5.6)	44.2 (5.2)	60.2 (5.3)	73.3 (3.7)	81.5 (3.7)	82.7 (3.7)	78.7 (4.3)	70.3 (4.2)	54.5 (4.6)	39.6 (6)	30.3 (6)
TD											
2014	10.7 (3.2)	21.3 (4.4)	50.1 (4.9)	67.5 (4.2)	81.1 (3)	85.9 (2.5)	80.8 (3.7)	62.9 (5.9)	38.7 (5.6)	17.9 (3.9)	11.2 (3.2)
2016	15.4 (2.9)	28.4 (4)	63.2 (4.4)	77.7 (3.7)	86.9 (2.7)	89.9 (2.3)	88.2 (3.3)	62.3 (5.3)	40.6 (5)	21.1 (3.4)	11.2 (2.8)

Note. Numbers in parentheses are standard errors of the mean. Negative SOAs reflect VA sequences, while positive SOAs reflect AV sequences. SJT = simultaneity judgment task; SOA = stimulus onset asynchrony; H-SLI = history of specific language impairment; TD = typical development; VA = visual-auditory; AV = auditory-visual.

intelligence. Fathers of children with H-SLI had significantly fewer years of education. This group difference did not extend to mothers' education. Compared with their peers with TD, children with H-SLI had more behavioral problems related to attention (on the basis of the ADHD Index). Although most children with H-SLI scored above the clinical cutoff on CELF-4, as a group, they still performed significantly worse than their peers with TD on most CELF-4 subtests, with the Recalling Sentences task proving the most difficult. Also, the number memory test (Test of Auditory Processing Skills) and the nonword repetition test were both more challenging for children with H-SLI than for their peers with TD. In fact, on nonword repetition, the group difference was already significant for two-syllable nonwords. All of the above results replicate our findings from the 2014 study, showing that both cohorts of children (from 2014 and 2016) had comparable language,

Table 3. Group differences in performance on the SJT.

Analysis	2014		2016	
	<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
VA Group × SOA	6.8 (5, 140)	.001	6.3 (5, 180)	.002
SYNC	<1		3.8 (1, 37)	.059
VA 100	<1		1.4 (1, 37)	.243
VA 200	3.1 (1, 29)	.091	<1	
VA 300	3.1 (1, 29)	.087	<1	
VA 400	16.3 (1, 29)	<.001	5 (1, 37)	.032
VA 500	18.5 (1, 29)	<.001	6.6 (1, 29)	.014
AV Group × SOA	5.3 (5, 140)	.009	6.4 (5, 180)	.001
SYNC	<1		3.8 (1, 37)	.059
AV 100	<1		3.4 (1, 37)	.074
AV 200	2 (1, 29)	.166	1.2 (1, 37)	.289
AV 300	13.5 (1, 29)	.001	3.2 (1, 37)	.082
AV 400	10 (1, 19)	.005	6.4 (1, 31)	.016
AV 500	11.5 (1, 17)	.003	7.2 (1, 28)	.011

Note. Numbers in parentheses are degrees of freedom. When groups' variances were not equal, the Brown-Forsythe robust test of equality of means was applied, which is reflected in reduced degrees of freedom for some comparisons. The *p* values below $\alpha = .05$ are shown in boldface. SJT = simultaneity judgment task; VA = visual-auditory; SOA = stimulus onset asynchrony; AV = auditory-visual; SYNC = synchrony (i.e., 0 ms SOA).

Figure 2. Performance on the simultaneity judgment task: a within-group comparison. Error bars are standard errors of the mean. Note that lines connecting individual data points in each group do not reflect a fitted function and are included only for ease of viewing. TD = typical development; H-SLI = history of specific language impairment; SOA = stimulus onset asynchrony; VA = visual-auditory; AV = auditory-visual.

Table 4. The size of VA and AV TBWs.

Group	TBW (ms)	
	VA	AV
H-SLI	455 (23)	438 (26)
TD	343 (22)	318 (24)

Note. Numbers in parentheses are standard errors of the mean. VA = visual-auditory; AV = auditory-visual; TBW = temporal binding window; H-SLI = history of specific language impairment; TD = typical development.

working memory, attention, and socioeconomic status characteristics.

Performance on the SJT

Figure 1 and Table 2 summarize groups' performance on the SJT. The main focus of our statistical analysis was on the interaction between group and SOA. Table 3 summarizes its outcome. In both the 2014 and 2016 studies, children with H-SLI were significantly more likely to perceive asynchronous audiovisual stimuli as synchronous at the two largest SOAs of 400 and 500 ms, regardless of the order of auditory and visual modalities. In absolute terms, the group difference was stronger in the 2014 data set, yet the overall pattern of group effects remained very consistent. In addition to the number of synchronous perceptions, I also examined the number of misses in each group. Note that there was no group difference or a Group $\times$ SOA interaction in the number of misses in either study, all $F_s \leq 1.898$, all $p_s \geq .124$.

Figure 2 directly compares the performance of each group of children in 2014 and 2016. Statistical analyses showed that children with H-SLI had virtually identical

responses in both studies, with no significant effect of group for either VA or AV SOAs, $F(1, 32) < 1$, and no Group $\times$ SOA interactions for either modality sequence, $F(5, 160) < 1$. Children with TD overall performed very similarly in both studies; however, the 2016 group did significantly worse on the VA SOAs, group $F(1, 32) = 4.9$, $p = .034$, $\eta_p^2 = .133$. This effect did not interact with SOA, $F(5, 160) < 1$. In sum, children tested in the 2016 study performed overall very similarly to the children tested in the 2014 study. The only significant difference was present in children with TD, who tended to perceive synchrony on more trials in the 2016 study during VA SOAs. However, this difference did not alter the overall pattern of relationship between groups with H-SLI and TD. As such, the 2014 and 2016 cohorts were collapsed for all remaining group analyses.

TBW's

Table 4 reports the size of VA and AV TBWs in each group. Figure 3 contains graphs of TBWs from one representative participant in each group. Children with H-SLI had a significantly larger TBW compared with their peers with TD, $F(1, 60) = 13.2$, $p = .001$, $\eta_p^2 = .18$. The Group $\times$ TBW Side interaction was not significant, $F < 1$, nor was there an effect of a modality order, $F(1, 60) = 2.6$, $p = .11$.

Regressions

The outcome of multiple regression analyses is shown in Table 5. In Figure 4, relationships between each of the predictor variables and the dependent variable are plotted in separate graphs. In all models, a combination of audiovisual temporal processing skills and attention skills accounted for approximately 23%–37% of variability in children's linguistic ability, on the basis of R^2 . The relationship between predictor and dependent variables was always

Figure 3. Temporal binding windows (TBWs). TBWs from one representative child in each group are shown. Note that TBW was measured at 40% of the maximum. Negative SOAs represent VA stimuli, while positive SOAs represent AV stimuli. The y-axis shows the proportion of synchronous perceptions. H-SLI = history of specific language impairment; TD = typical development; VA = visual-auditory; AV = auditory-visual; SOA = stimulus onset asynchrony.

Table 5. Multiple regression results.

Predictors	Unstandardized coefficients		95% confidence interval for <i>b</i>		Standardized coefficients	<i>t</i>	Significance
	<i>b</i>	<i>SE</i>	Lower bound	Upper bound	β		
ADHD Index	-.455	.148	-.749	-.16	-.336	-3.079	.003
AV400-AV500	-.224	.064	-.353	-.096	-.382	-3.497	.001
Model's $R^2 = .369$							
ADHD Index	-.486	.16	-.805	-.166	-.359	-3.034	.003
VA400-VA500	-.175	.072	-.319	-.031	-.286	-2.42	.018
Model's $R^2 = .313$							
ADHD Index	-.479	.165	-.809	-.148	-.354	-2.9	.005
AV TBW	-.021	.01	-.04	-.001	-.257	-2.106	.04
Model's $R^2 = .265$							
ADHD Index	-.539	.168	-.875	-.203	-.399	-3.21	.002
VA TBW	-.014	.011	-.037	.009	-.151	-1.217	.229
Model's $R^2 = .229$							

Note. In each model, the dependent variable was the Core Language Score (CLS) from the Clinical Evaluation of Language Fundamentals–Fourth Edition. AV400-500 refers to the average of synchronous perceptions across the two longest AV SOAs (i.e., 400 and 500 ms). VA400-500 refers to the average of synchronous perceptions across the two longest VA SOAs (i.e., 400 and 500 ms). $n = 68$ for the top two models; $n = 62$ for the bottom two models. ADHD = attention-deficit/hyperactivity disorder; AV = auditory-visual; VA = visual-auditory; TBW = temporal binding window.

negative, meaning that a higher ADHD Index (i.e., more attention issues), a higher number of synchronous perceptions at the longest SOAs, and a larger TBW was associated with lower language skills, as measured by CLS. Standardized coefficients (beta), which are directly comparable, indicate that children's performance on the two longest SOAs, in both AV and VA sequences, accounts for a larger portion of variation in children's language skills compared with the TBW size. In fact, in the model with the VA TBW as a predictor, the influence of the TBW size on CLS failed to reach significance (see the bottom model in Table 5) at $\alpha = .05$.

Discussion

In this study, I replicated our earlier findings of reduced sensitivity to audiovisual temporal asynchrony in school-age children with H-SLI. This successful replication shows that our previous article is valid and reveals a true area of weakness in this population, which, up until now, had not received much attention. Following this replication, I was able to combine data from both studies and examine the relationship between audiovisual temporal function, attention, and language in a larger group of children. I found that better performance on the SJT and better attention were significantly correlated with better language skills. The relationship between audiovisual temporal processing and language skills was particularly strong when the former was measured by the number of synchronous perceptions at the longest SOAs (400 and 500 ms) rather than by the TBW. This outcome was likely because the groups differed the most over the longest SOAs, which was not well captured by the TBW, even when it was measured at 40% of the maximum.

In developmental literature, large TBWs in younger children and infants are interpreted as a sign that they

integrate auditory and visual modalities into a single event over longer temporal separations. However, as children gain more experience interacting with the world around them, their TBW slowly diminishes, allowing for a more precise matching between senses. Within this context, one interpretation of our findings may be that children with H-SLI are more likely than children with TD to integrate auditory and visual stimuli in a unified percept, even at very long SOAs, which results in the (incorrect) perception of synchrony. In other words, the deficit lies in the neural integrative mechanisms, which may be abnormal or immature in this group.

However, other interpretations of the results are possible. In particular, poorer performance by the children with H-SLI on the SJT may be driven by weaker attentional skills in this group. Earlier work shows that sensitivity to temporal information and attention are related. In children with TD, temporal precision correlates strongly with attentional skills and working memory (Zélandi & Droit-Volet, 2011). In the same vein, children with ADHD have been shown to perform poorly on temporal judgment (Radonovich & Mostofsky, 2004) and time discrimination (Rubia, Smith, & Taylor, 2007) tasks. Previous studies show that some aspects of attention in both the auditory (Finneran, Francis, & Leonard, 2009; Stevens, Sanders, & Neville, 2006) and the visual (Dispaldro et al., 2013; Victorino & Schwartz, 2015) domains are indeed impaired in SLI. This interpretation would suggest that audiovisual integrative mechanisms as such may be spared in children with H-SLI and could function normally if sufficient attentional resources are allocated to the temporal relationships between auditory and visual stimuli.

Also, poor sensitivity to audiovisual temporal asynchrony in the H-SLI group may be due to difficulty in making explicit temporal judgments required by the SJT.

Figure 4. Regressions. In multiple regression analyses, Core Language Score (CLS) was always entered as a dependent variable, while the attention-deficit/hyperactivity disorder (ADHD) Index and measures of audiovisual temporal function were entered as predictor variables (for statistical results, see Table 5). AV = audiovisual; SOA = stimulus onset asynchrony; VA = visual-auditory; TBW = temporal binding window.

Indeed, explicit and implicit timing skills show different developmental trajectories (Droit-Volet & Coull, 2016), with explicit skills continuing to develop during school years. Explicit and implicit timing have also been shown to engage somewhat disparate brain regions (for a review, see Droit-Volet, 2013). Although most studies of timing skills in children required judgments about the duration of temporal intervals rather than the simultaneity of stimuli's onsets, the latter is still based on the ability to judge a temporal relationship between two events and thus is not entirely dissimilar from other temporal tasks. The group difference observed on the SJT in this study could then be due to the difficulty with overt temporal judgments in children with

H-SLI. This interpretation would suggest impairment in the neural mechanisms underlying temporal function more generally and may also indicate that implicit temporal processing is normal in this group, although this hypothesis would require future testing.

Related to the above point is the question of whether difficulty in simultaneity judgment observed in children with H-SLI is specific to multisensory stimuli or if it generalizes to auditory only and/or visual only sequences. Perception of unimodal sequences by children with SLI has been studied in detail (Tallal & Piercy, 1973; Tallal, Stark, & Mellits, 1985a, 1985b). Many authors reported impaired ability of children with SLI to process either brief sounds or sounds

presented in a fast succession, although the mechanisms underlying this deficit are still a matter of debate. However, the lengths of our stimuli (i.e., 200 ms) and of the SOAs at which groups differed the most (400–500 ms) well exceed those typically seen as problematic for children with SLI. In other words, on the basis of previous research, we would not expect children with H-SLI to struggle with asynchrony detection at SOAs of 400–500 ms. It is more likely, therefore, that the difficulty we observed is closely tied to multisensory processing.

Whatever the underlying cause, a lack of precision in audiovisual temporal processing may pose a significant disadvantage for children with H-SLI. Our regression analyses revealed a strong connection between audiovisual temporal function and language skills. Although this outcome does not imply causation, it warrants further research. Successful integration of auditory and visual senses provides significant benefits during a number of tasks, including speech-in-noise perception, the task that we encounter on a daily basis. In addition, accumulating evidence strongly suggests that many aspects of language acquisition, such as phoneme perception (Teinonen et al., 2008) and word learning (Hollich et al., 2005; Jesse & Johnson, 2016), are audiovisual in nature. Because temporal proximity between different modalities is a key prerequisite for successful audiovisual integration, understanding why children with H-SLI have poor audiovisual temporal function might inform the development of future intervention techniques that would focus on its improvement. Earlier studies in adults show that this function can be readily enhanced through training (Powers, Hevey, & Wallace, 2012; Powers, Hillock, & Wallace, 2009).

Note that in addition to audiovisual temporal processing, attention also accounted for a significant portion of variability in children's linguistic skills. Although attention and performance on the SJT were correlated, measures of multicollinearity (VIF) in the regression models suggested that this relationship was not strong enough to pose problems for the interpretation of the results, or put a different way, our two predictors (SJT and ADHD Index) measured different things. The importance of attention for language skills remains understudied, especially in developmental language disorders. Specific linguistic mechanisms affected by attention may be many and require future research. As one example in a recent study, Astheimer, Janus, Moreno, and Bialystok (2014) showed that the degree of attentional allocation to word onsets during speech perception in 5-year-olds predicted their grammaticality judgment accuracy, suggesting that effective allocation of attention to speech can enhance not only perceptual but also complex metalinguistic skills. At present, to the best of our knowledge, no studies on attention to multisensory events in SLI exist. This area is in great need of future studies.

In conclusion, children with H-SLI are impaired at detecting audiovisual temporal asynchrony. Note that audiovisual temporal function and attention predict up to 37% of variability in children's language skills, with more precise temporal function and better attention corresponding

to stronger language ability. These findings support the possibility of using audiovisual temporal training to improve language skills in school-age children with H-SLI.

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