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Grammaticality sensitivity in children with early focal brain injury and children with specific language impairment

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Abstract

Grammaticality judgments and processing times associated with violation detection were examined in typically developing children, children with focal brain lesions (FL) acquired early in life, and children with specific language impairment (SLI). Grammatical sensitivity in the FL group, while below typically developing children, was above levels seen in children with SLI. Age effects were noted with developmental changes in sensitivity extending into adolescence. Developmental delays in grammatical processing were particularly pronounced for children with SLI, who showed sensitivity levels below those of younger typically developing children. Sensitivity to agreement violations was also protracted in the SLI group providing further evidence of the vulnerability of morphology, a pattern not unlike that seen in adult aphasics. Findings for the FL group provide compelling evidence of neural and behavioral plasticity in children with early unilateral brain injury. Moreover, results from these children underscore how very different compensatory organization may be compared to profiles seen in adult aphasics who have comparable lesions. In contrast, although it was expected that the SLI children would perform below the typically developing children, the disadvantage seen with respect to the FL group suggests that the underlying pathology responsible for SLI may be more pervasive and less plastic than the focal pathology of children with early brain damage.

Keywords: Language development; Grammaticality judgments; Specific language impairment; Early brain injury

1. Introduction

The purpose of this study is to compare on-line grammatical processing in two clinical populations, children with specific language impairment (SLI) and children with congenital focal brain lesions (FL), to performance by typically developing control children. We focus on morphosyntax because limitations in grammatical abilities are among the most common and persistent features in SLI, one of our study populations. Furthermore, problems with morphology and syntax are also common in adults with aphasia with unilateral brain lesions due to stroke that are comparable to the lesions seen in our study population of FL children. By comparing grammatical sensitivity between children with frank neurological impairment and children with language impairment who have no obvious brain damage, we hope to better understand the neural correlates of language disorders in general, and morphology and syntax in particular. Also, examination of profiles in these groups for evidence of variation in patterns of language learning may elucidate the constraints on neural plasticity and development.

While language develops effortlessly in most children, there are some who struggle with language learning. Despite much research, questions remain concerning causes and characteristics of specific language impairment (SLI). Researchers have sought to determine whether all aspects of language are affected, and whether deficits are delayed or deviant compared to typical children (Johnston & Kamhi, 1984; Lahey & Edwards, 1999; Menyuk, 1999; Schwartz & Leonard, 1985).

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Grammatical morphology is particularly challenging for children with SLI and includes difficulty marking verb inflections, using the auxiliary system and detecting grammatical violations (Bishop, 1994; Leonard, Eyer, Bedore, & Grela, 1997; Marchman, Wulfeck, & Ellis Weismer, 1999; Rice, Wexler, & Cleave, 1995; Rice, Wexler, & Redmond, 1999). According to some accounts, grammatical problems arise because certain innate features of grammar are inaccessible to SLI children (Gopnik & Crago, 1991). Others explain these grammatical deficits in terms of maturational delays (Rice et al., 1995). Verbal memory deficits also have been implicated (Dollaghan & Campbell, 1998; Gathercole & Baddeley, 1995; Montgomery, 1995; Sininger, Klatzky, & Kirchner, 1989; van der Lely & Howard, 1995). Tallal and colleagues have attributed SLI to limitations in basic auditory perceptual mechanisms critical for language (Merzenich et al., 1996). Still others have attributed SLI to limitations in processing speed or capacity, or to general processing deficits (Ellis Weismer, 1996; Kail, 1994; Leonard, 1998; Windsor & Hwang, 1999).

Often, performance of children with SLI resembles that of younger typically developing children. This suggests that delay rather than deviancy best characterizes language impairment, with persistent difficulties noted for grammatical morphology and syntax throughout childhood. For example, our study of narratives (Clifford, Reilly, & Wulfeck, 1995) revealed that SLI children made morphological errors and used less complex syntax, yet were able to convey the story theme, a pattern similar to younger typically developing children.

Notably, these oft-cited deficits in the access and use of grammatical morphology in children with SLI are similar to those reported for adult aphasics (Goodglass, 1993). At first glance there might not appear to be any apparent relationship between aphasia and SLI. However, there has been long-standing interest in the degree to which aphasia represents a regression of language abilities and whether recovery parallels the developmental progression seen in early language acquisition. Despite this interest, only a small number of language studies have compared the performance of adult aphasics to that of typical children (e.g., Naeser et al., 1987; Parisi & Pizzamiglio, 1970). For example, Naeser et al. (1987) examined comprehension of 10 syntactic structures in aphasia subgroups and two age groups of typically developing children. Their findings indicated that performance between adults and children differs in degree but not in the order of difficulty of syntactic constructions. Performance of the youngest children was similar to the most impaired adults and performance of the older children compared to the least impaired adults.

These parallels between adults with aphasia and children with SLI might lead us to expect close mappings between the language profiles of SLI children and those seen in FL children who have brain lesions comparable to adult aphasics. However, as we shall see, studies of language development in FL children have yielded surprising results.

Researchers have been both encouraged and puzzled by the language abilities of FL children. They are encouraged because there appears to be great potential for development in children with very early focal brain injury. At the same time, the emerging profiles are puzzling because they bear little relationship to adult models of aphasia. Although the literature is relatively small due to the rarity of the FL population, there is growing evidence that these children develop language within the average or low-average range, demonstrating remarkable evidence of neural plasticity (Bates, Vicari, & Trauner, 1999; Bates et al., 1997; Feldman, Holland, Kemp, & Janosky, 1992; Reilly, Bates, & Marchman, 1998; Vargha-Khadem, Isaacs, & Muter, 1994; Wulfeck, Trauner, & Tallal, 1991b). Also, contrary to what might be expected based on the adult aphasia literature, language abilities in children with FL are similar whether the lesion is in the left hemisphere (LH) or right hemisphere (RH). Moreover, studies comparing language abilities in children with RH or LH lesions to performance of adults with aphasia with comparable LH lesions, reveal that language production (Bates et al., 2001) and comprehension (Kempler, van Lancker, Marchman, & Bates, 1996) were within the normal range for the children. Also, no significant lesion side differences were observed.

To fully understand language development we must go beyond what children *know* about language and examine temporal aspects of language processing (i.e., *when* specific parsing decisions are made, *how* decisions are affected by contextual information). Our rationale for studying grammatical processing comes from three different sources: (1) the development of grammatical abilities in children, (2) the vulnerability of grammatical morphology in aphasia, and (3) the protracted development of, and persistent problems with, grammar in children with SLI.

Results of real-time sentence processing in typically developing children (Friederici, 1983; Roe et al., 2000; Tyler & Marslen-Wilson, 1981; von Berger, Wulfeck, Bates, & Fink, 1996) indicate that with development, children become faster and more efficient at integrating increasingly complex sources of linguistic information. Developmental studies of grammatical sensitivity have focused on when children acquire grammatical rules and how rules are used. For example, studies have explored the ability of children to differentiate grammatical from ungrammatical sentences and to repair ungrammatical sentences (Clark, 1978; de Villiers & de Villiers, 1972; Sutter & Johnson, 1990). Results indicate a developmental progression with youngest children attending to semantic and plausibility aspects of language while older children pay attention to morphosyntactic forms.

We examined grammatical processing in two age groups of typically developing children (Wulfeck, 1993). Children heard grammatical sentences and ungrammatical sentences with various violations and were asked to perform a judgment task. While both groups showed very good grammatical sensitivity, older children outperformed younger children, although at lower levels compared to adults (Wulfeck, Bates, & Capasso, 1991a). Results revealed that children were better at detecting word order compared to agreement violations. Since adults were equally sensitive to both violation types, the study revealed both qualitative and quantitative differences in grammatical sensitivity across the school years. Finally, older children processed violations more quickly and decision time results indicated that greater sensitivity to word order compared to agreement violations enhanced their ability to take advantage of context across a sentence.

Interestingly, these developmental findings are consistent with results from a similar study we conducted with Broca's aphasics investigating whether the ability to detect grammatical violations was related to agrammatic production commonly observed in this population (Wulfeck & Bates, 1991). Results indicated that adults with Broca's aphasia retain some degree of grammatical sensitivity and that they are able to use this knowledge "on-line." However, as with our developmental study, performance was affected by violation type. Broca's aphasics were less sensitive to agreement compared to word order violations providing further evidence of the vulnerability of grammatical morphology in aphasia.

Blackwell and Bates (1995) induced agrammatic performance profiles in healthy adults in a dual task paradigm by asking participants to judge grammaticality while holding digits in memory. Under these conditions, movement errors were resilient, agreement errors were vulnerable and omission errors fell in between. Blackwell and Bates (1995) suggest that vulnerability of morphology in aphasia may be due to capacity limitations rather than a selective lesion. In a related study, Blackwell, Bates, and Fisher (1996) examined the time course for detecting violations of movement, agreement and omission using three different techniques. All three methods yielded similar results with the time course for violation detecting varying by violations type. To illustrate, consider a grammatical sentence like "She is selling books at the fair." An agreement violation for this sentence might be "She are * selling books at the fair," a movement error would be "She selling is * books at the fair," while the equivalent omission error would be "She selling * books at the fair." Although participants were more likely to miss an agreement error altogether, judgments were made quickly when an error was noticed. In contrast, omission errors were resolved within a long and variable time window spanning several words after the omission had occurred. Movement errors fell midway between, and were usually resolved at the point where the moved element is encountered. These differences were exacerbated when errors occurred early in the sentence; for late occurring errors, judgments were made quickly and accurately for all violation types. These results suggest that the hierarchy of accuracy (movement > omission > agreement) is different from the hierarchy for reaction times (agreement < movement < omission).

Only a handful of studies of on-line language processing have been conducted with children with developmental language impairment. Montgomery and colleagues (Montgomery, Scudder, & Moore, 1990; Stark & Montgomery, 1995) noted slower word recognition in their SLI group and interpreted findings as evidence of difficulties in lexical access and resource allocation. By contrast, in a language study of children with focal brain lesions, only minimal effects of brain damage were observed (MacWhinney, Feldman, Sacco, & Valdes-Perez, 2000). Recently, we examined complex sentence interpretation abilities in typical, FL and SLI groups and in healthy and aphasic adults (Dick et al., 1999b). Overall, results revealed a hierarchy of abilities, with best performance by typical children and adults followed by the FL group and anomic adults. Poorer performance was seen in the SLI group who showed a profile strikingly similar to the Broca's aphasic group.

From previous reports, it appears that the acquisition of language knowledge and the ability to use language in an efficient manner may operate under somewhat different developmental timetables. We have also seen that grammatical morphology is vulnerable under conditions of brain damage in aphasia and presents persistent problems for children with language impairment. In contrast, the language system in children with FL, who share neurologic features with aphasic adults, may be more resilient to effects of brain damage.

This brings us to the purpose of the present study, which is to compare real-time grammaticality judgment abilities in typically developing, SLI and FL children. We use sentence stimuli developed by Blackwell and Bates (1995), incorporating violations of word order, agreement and omission involving different parts of speech, noun determiners and auxiliary verbs. In the English language, cues (e.g., word order, subject–verb agreement) used to guide sentence processing differ in information value (Bates & MacWhinney, 1989). Because of their structural properties, the three target error types may also differ in cue cost (i.e., the amount of resources needed to use a cue—the more salient the cue, the less costly during processing). Also, structural differences between noun determiners and auxiliary verbs may impose differing processing demands. As a result of the linguistic and processing constraints imposed by this task, performance from our typically developing children can be used as a benchmark from which to examine differential strengths and weaknesses in our two clinical populations.

Examination of real-time grammatical processing in SLI children offers an opportunity to determine whether differences exist in sensitivity to violations (i.e., knowledge) and/or in detection time (i.e., processing). Studies to date suggest that both aspects of grammatical development are at risk in the SLI population. At the same time, findings for FL children reveal a remarkable capacity for language that is in sharp contrast to that seen in adult aphasics with comparable lesions. However, because language trajectories have only been sparsely mapped in these children, it is not yet clear whether all aspects of language are immune to the effects of early focal brain injury. By examining on-line language processing in our FL group, vulnerabilities (grammatical knowledge, processing or both) may be revealed that are not apparent in language studies that impose few processing constraints. In sum, our study of three contrasting groups of children will permit us to address key issues pertaining to language acquisition and neuroplasticity: (1) the development of grammaticality sensitivity and processing, (2) the vulnerability of grammatical processing in children with SLI, and (3) the impact of early focal brain injury on grammatical processing.

2. Materials and methods

2.1. Participants

Seventy-eight monolingual English-language speaking children, ages 7–12 years, from three populations participated in this study. This included 34 typically developing control children (TD), 28 children with specific language impairment (SLI) and 16 children with focal brain lesions (FL). Children from the three study populations were divided into three age groups: 7/8, 9/10, and 11/12 years of age and an analysis of variance confirmed that the groups were balanced for age. Prior to participation, children underwent screening at our Center to ensure that they had hearing and vision within normal limits and that they met selection criteria for their group.

The parents of the TD children completed questionnaires confirming normal developmental and educational histories and grade level performance in school. In addition, children underwent testing to insure within normal performance in language and cognition.

Children in the SLI group had a documented language impairment and were recruited from speech-language pathologists and physicians. Following testing in our laboratory, children were inducted into our study if they met the following selection criteria: (1) performance I.Q. (PIQ) of 80 or higher on the WISC-R (Wechsler, 1974) or the Leiter (1948) measures, (2) no major neurological abnormalities (determined by a neurological examination), (3) expressive language composite score 1.5 or more standard deviations below the mean using the CELF-R (Semel, Wiig, & Secord, 1987), and (4) absence of developmental disorders, such as autism.

Children in the FL group, recruited from pediatric neurologists and pediatricians, were examined by a pediatric neurologist and were inducted if they had the following characteristics: (1) evidence of a unilateral left or right-hemisphere focal lesion, (2) lesion onset was prenatally, perinatally or within the first 6 months of life, and (3) identification of lesion site based on CT, MRI or both. In the present study, 16 FL children, 11 with left-hemisphere damage (LHD) and 5 with right-hemisphere damage (RHD) participated.

In this study, we faced several subject matching challenges. Due to the inherent difficulties finding sufficient numbers of children from our clinical populations who met our selection criteria, our groups are small and unequal. In addition, we faced difficulties balancing gender across groups because of the usual male bias in the SLI population. However, it was not necessary to drop children from any group to achieve complete gender balance since analyses of variance conducted on test scores and the two dependent measures (grammatical sensitivity and reaction time) confirmed that there were no significant differences across the three groups with respect to gender.

Second, while children with SLI by definition meet selection criteria with respect to adequate performance IQ (PIQ), there are no such selection criteria for the FL group. Instead, FL children are defined by their neurological impairment and related exclusionary criteria. We have no a priori reason to exclude individual FL children from the study based upon PIQ, as long as they can successfully complete our experimental task. In preliminary analyses, however, we noted that 5 of the 16 FL children had PIQs below 80. We conducted an analysis of variance with group and age. Neither the main effect of age nor the interaction of age and group were significant, however, there was a significant group difference $[F(2,68) = 9.894,\ p < .001]$ with the TD group showing a PIQ advantage ($M = 112$) compared to the SLI ($M = 100$) and FL groups ($M = 94$), who did not differ from each other. This same pattern was observed even when we removed the 4 FL children with PIQs < 80 from the analyses. As a result, we decided not to exclude any participants but to use PIQ as a covariate in subsequent analyses of grammatical sensitivity. Table 1 shows the age, non-verbal intelligence and language scores of our groups.

We received parental consent for all children. Institutional Review Boards at the University of California,

Table 1
Means and standard deviations for age (years/months) and standard scores for the WISC-R or the Leiter Performance IQ and CELF-R expressive languages (ELS), receptive language (RLS) and total language (TLS) scores for typically developing (TD), focal lesion (FL), and specific language impaired (SLI) groups

Group	Age (*SD*)	PIQ (*SD*)	ELS (*SD*)	RLS (*SD*)	TLS (*SD*)
TD	9;9 (1;7)	111.7 (11.7)	97 (8.1)	104.2 (13.3)	100.4 (10.2)
FL	9;5 (1;9)	70.7 (20.4)	70.7 (20.4)	84.1 (13.5)	77.9 (13.6)
SLI	9;2 (1;8)	100.4 (11.3)	64.6 (8.9)	71.7 (12.2)	66.2 (9.6)

San Diego and San Diego State University approved our protocol.

2.2. Stimulus design and development

Stimuli for the grammaticality judgment task were 168 sentences: 84 ungrammatical sentences, 40 grammatical sentences matched for length and grammatical structure, and 44 fillers (see Blackwell & Bates, 1995 for details regarding stimulus development). The experimental design focused on the ungrammatical targets, which varied in: (1) Word Class of the violation (auxiliary or determiner), (2) Position of the violation (early or late in the sentence), and (3) Type of violation (movement, omission, or substitution).

The ungrammatical sentences formed a 2 × 2 × 3 design, with position, word class and violation type as within-subject variables. Each of the 12 cells within this design contained seven ungrammatical sentences. For each ungrammatical sentence, children heard a grammatical control sentence. To keep the length of the experiment within reasonable bounds, some of the grammatical sentences were used as controls for more than one ungrammatical sentence. Filler sentences (22 grammatical and 22 ungrammatical) 3–17 words long and of various structures were included to prevent children from detecting regularities in the target sentences.

The 84 ungrammatical targets (examples in Table 2 below) and 40 grammatical controls were selected from a pool of grammatical sentences ranging from 8 to 12 words long. This pool represents seven sentence structure types varying in presence and location of prepositional phrases, presence or absence of relative clauses or subordinate clauses, and the number of adjectives modifying the subject and object. Approximately 20 different grammatical sentence tokens were constructed for each of the seven structural types, and randomly assigned to the appropriate ungrammatical target cell or grammatical control condition.

2.2.1. Word class manipulation (auxiliary vs. determiner)

Half of the sentences had at least one auxiliary verb that was the target of an auxiliary violation, while the other half of the sentences had at least one determiner (including numerals and demonstrative adjectives) to be the target of a determiner violation. Auxiliary verbs were located early in a sentence or near the end of a sentence. The target determiner was located either early in the sentence or was located near the end of the sentence.

2.2.2. Violation position manipulation (early vs. late in the sentence)

Early errors occurred within the first 1200 ms of the sentence, while late errors occurred after this point. The

Table 2
Sample ungrammatical sentences for the 12 stimulus cells

Part of speech	Type of error	Position of error	
		Early	Late
Auxiliary	Omission	Mrs. Brown working * in the church kitchen	She had written that mystery novel that her mother reading *
	Substitution	The writer were * holding a very big party	While sitting on the couch, Mr. Lane's daughters was * watching a movie
	Movement	Miss Hope sending * was several green dresses that Lisa had ordered	While talking to Jane, Joseph knitting * was a sweater
Determiner	Omission	Girl * was working quietly near the small, red house	The small, thin green vine was sprouting flower *
	Substitution	A boys * are driving a large van that the artist has painted	Larry is saying that his mother was planting that bushes *
	Movement	Helicopter * a was hovering loudly over the army base	Those girls were watching the bright lightning while camping in desert * that

Note. The asterisk (*) is placed at the first point at which ungrammaticality might be noticed.

licensing word and the error were always adjacent (i.e., all local errors).

2.2.3. Violation type manipulation (movement, omission, or substitution)

Movement errors were created by moving the relevant word one word downstream from where it belonged. Omission errors were created by removing the relevant word (auxiliary or determiner) from the sentence. Substitution errors were created by replacing the target word with an item that did not agree in number. Table 2 contains examples of ungrammatical sentences for the 12 stimulus cells.

2.3. Experiment preparation and administration apparatus

Sentences were recorded by a native English speaker. Stimuli were digitized and the experiment was administered via computer using PsyScope, a dynamic experiment control system developed by Cohen, MacWhinney, Flatt, and Provost (1993). Judgments and decision times were recorded via either of two response buttons mounted on a button box that has a timer for interval measurements accurate to 1 ms that connects to the computer.

2.4. Procedures

The experiment consisted of 168 trials of the sentence stimuli described above. The sentences were arrayed in a Latin Square design, with the constraint that no two items from the same cell (e.g., early determiner omission) could appear consecutively, and no two fillers could appear consecutively. Each child was tested in a quiet room. The experimenter sat next to the child, controlling the computer so that it could be stopped if the child needed a break or reminders to respond quickly. First, the child practiced button pressing to become familiar with the apparatus. A 30-item baseline RT task was also administered in which the child heard the word “good” or “bad” and pushed either of two buttons on which was written “good” (under a smiling face) or “bad” (under a frowning face).

Next, each child was administered 20 practice sentences for the grammaticality judgment task. Training items were similar but not identical to test sentences. The child was instructed to indicate whether or not a sentence “has good grammar” by pushing either of the two buttons (“good” or “bad”) on the button box. In other words, children were asked to accept grammatical sentences (“good”) and reject ungrammatical ones (“bad”). Children were instructed to listen carefully since they would only hear each sentence once and to respond as quickly as possible, even if a sentence was still running. A trial consisted of the following: the sentence was played, followed by a fixed 3000 msec window for participants to make a button press. Both accuracy and reaction times (RTs) were collected for each trial.

2.5. Data reduction

As a first step to analysis, “No response” trials were removed. Consistent with previous work (Wulfeck, 1993), children performed the task easily, failing to make a judgment on less than 5% of the sentences. In this study, only one child (FL group) could not complete the task and this child was at the youngest test age (7 years).

Next, for each of the 12 cell conditions for each participant, proportions of hits (correctly rejecting an ungrammatical sentence) and false alarms (incorrectly rejecting a grammatical sentence) were calculated. Perfect sensitivity occurs when all ungrammatical sentences are rejected (hit rate = 1.00) and no correct sentences are rejected (false alarm rate = 0). A's were then calculated from both the hit and false alarm rates. A' is a nonparametric statistic used to correct for response bias (Blackwell & Bates, 1995; Grier, 1971; Pollack & Norman, 1964). For a two-alternative forced-choice task, the A' statistic estimates the proportion correct. Perfect discrimination yields an A' of 1.00 and chance performance yields an A' of .50.

Reaction time (RT) analyses were conducted on median RTs and were limited to those items that were correctly rejected as ungrammatical. The reaction times represented a child’s button-pressing time, in milliseconds (measured from the offset of the word just before the violation point) minus the child’s mean baseline reaction time. In the RT analyses reported here, reactions times have been adjusted by subtracting a child’s mean baseline RT from each response in order to partial out developmental differences in motor speed.

3. Results

In this section we present analyses of the grammaticality judgment (A's) and median reaction time data for the three groups. Prior to conducting the group analyses, performance between FL children with left hemisphere damage (LHD) and those with right hemisphere damage (RHD) was compared and no significant lesion side differences were obtained on any measure. However, because sample sizes are small and unequal between the lesion subgroups, the absence of a lesion side effect should be interpreted with caution until this pattern is replicated in a larger sample. For purposes of the present study, in all analyses reported here, data from children with RHD and LHD are collapsed into a single FL group. Tables 3–5 contain the mean A' values and the mean median reaction times and standard deviations for the 12 sentence types for the three groups at each of the four age comparisons.

Table 3
Mean *A′* and median reaction times (ms) for TD children in three age groups

Sentence type	7–8 years		9–10 years		11–12 years	
	A′ (*SD*)	RT (*SD*)	*A′* (*SD*)	RT (*SD*)	*A′* (*SD*)	RT (*SD*)
EAM	.75 (.20)	1828 (789)	.88 (.13)	1329 (833)	.98 (.03)	1264 (653)
EAO	.79 (.16)	1801 (823)	.89 (.13)	1550 (984)	.96 (.06)	1138 (544)
EAS	.74 (.16)	1608 (794)	.85 (.12)	1319 (960)	.92 (.04)	1067 (793)
EDM	.80 (.17)	1821 (876)	.89 (.12)	1515 (943)	.96 (.03)	869 (501)
EDO	.75 (.17)	1939 (1029)	.85 (.15)	1630 (1068)	.93 (.09)	1385 (897)
EDS	.73 (.13)	1794 (921)	.79 (.12)	1548 (986)	.86 (.10)	768 (400)
LAM	.82 (.18)	973 (372)	.89 (.12)	725 (626)	.99 (.02)	666 (280)
LAO	.80 (.19)	709 (436)	.89 (.15)	564 (467)	.96 (.05)	426 (227)
LAS	.81 (.20)	869 (433)	.90 (.13)	568 (334)	.97 (.04)	419 (199)
LDM	.84 (.19)	682 (506)	.90 (.12)	503 (310)	.98 (.03)	280 (148)
LDO	.80 (.17)	189 (434)	.88 (.15)	217 (439)	.99 (.02)	12 (206)
LDS	.85 (.18)	288 (526)	.91 (.08)	292 (365)	.95 (.05)	125 (213)
Means	.79 (.18)	1208 (662)	.88 (.13)	980 (693)	.95 (.05)	702 (422)

Sentence type is coded as follows: The first column denotes position (Early or Late); the second, violation type (Movement, Omission, and Substitution); the third, word class (Auxiliary, Determiner).

Table 4
Mean *A′* and median reaction times (ms) for FL children in three age groups

Sentence type	7–8 years		9–10 years		11–12 years	
	A′ (*SD*)	RT (*SD*)	*A′* (*SD*)	RT (*SD*)	*A′* (*SD*)	RT (*SD*)
EAM	.72 (.18)	1834 (404)	.88 (.09)	1809 (394)	.97 (.07)	1203 (754)
EAO	.67 (.22)	2129 (725)	.80 (.22)	2192 (971)	.88 (.12)	1644 (119)
EAS	.68 (.22)	2123 (511)	.66 (.19)	1607 (378)	.80 (.21)	1355 (813)
EDM	.81 (.16)	2237 (102)	.92 (.07)	2533 (797)	.83 (.18)	1515 (647)
EDO	.68 (.20)	2584 (333)	.76 (.24)	1634 (800)	.82 (.21)	1468 (1012)
EDS	.72 (.15)	2211 (802)	.68 (.12)	1819 (610)	.74 (.09)	1757 (394)
LAM	.66 (.19)	800 (381)	.81 (.23)	932 (196)	.93 (.05)	434 (304)
LAO	.73 (.17)	593 (179)	.84 (.23)	1037 (731)	.93 (.07)	214 (437)
LAS	.72 (.18)	756 (195)	.87 (.12)	713 (234)	.90 (.10)	634 (167)
LDM	.81 (.17)	667 (395)	.89 (.07)	371 (186)	.94 (.09)	245 (275)
LDO	.69 (.21)	205 (385)	.85 (.10)	231 (153)	.87 (.17)	−15 (297)
LDS	.69 (.22)	239 (335)	.83 (.14)	550 (493)	.87 (.21)	34 (330)
Means	.72 (.19)	1365 (396)	.82 (.15)	1286 (487)	.87 (.13)	874 (462)

Sentence type is coded as follows: The first column denotes position (Early or Late); the second, violation type (Movement, Omission, and Substitution); the third, word class (Auxiliary, Determiner).

Table 5
Mean *A′* and median reaction times (ms) for SLI children in three age groups

Sentence type	7–8 years		9–10 years		11–12 years	
	A′ (*SD*)	RT (*SD*)	A (*SD*)	RT (*SD*)	*A′* (*SD*)	RT (*SD*)
EAM	.55 (.12)	1932 (974)	.71 (.17)	1897 (407)	.81 (.15)	1270 (733)
EAO	.69 (.13)	2155 (890)	.64 (.14)	2194 (1084)	.78 (.13)	1470 (580)
EAS	.56 (.12)	2119 (640)	.66 (.17)	1254 (682)	.72 (.16)	1603 (457)
EDM	.63 (.16)	2570 (495)	.79 (.16)	1473 (835)	.74 (.23)	1457 (843)
EDO	.68 (.14)	2583 (436)	.69 (.19)	1390 (1351)	.75 (.23)	1375 (874)
EDS	.59 (.13)	2602 (607)	.70 (.17)	1956 (550)	.64 (.14)	1192 (833)
LAM	.62 (.14)	782 (605)	.64 (.20)	1063 (345)	.75 (.21)	703 (213)
LAO	.64 (.16)	617 (443)	.67 (.20)	1007 (254)	.73 (.18)	687 (208)
LAS	.63 (.14)	818 (516)	.76 (.19)	877 (479)	.67 (.18)	816 (615)
LDM	.70 (.15)	458 (471)	.84 (.15)	642 (429)	.87 (.13)	381 (130)
LDO	.63 (.13)	231 (337)	.70 (.20)	192 (502)	.79 (.20)	73 (92)
LDS	.68 (.14)	281 (531)	.75 (.16)	166 (432)	.80 (.15)	455 (441)
Means	.63 (.14)	1429 (579)	.71 (.18)	1176 (613)	.75 (.17)	957 (502)

Sentence type is coded as follows: The first column denotes position (Early or Late) the second, violation type (Movement, Omission, and Substitution); the third, word class (Auxiliary, Determiner).

3.1. Grammaticality judgment results

The mean (M) A' values for the three groups (TD, FL, and SLI) were analyzed in a 3 (Group) × 3 (Age) × 2 (Position) × 2 (Word Class) × 3 (Violation) repeated measures analysis of variance (ANOVA). Although all groups showed overall grammatical sensitivity above chance, there was a significant main effect for group $[F(2,69) = 17.097,\ p < .001]$ with the TD children displaying the highest overall grammatical sensitivity ($M\ A' = .87$), followed by the FL group ($M\ A' = .80$), and the SLI group displaying lowest sensitivity ($M\ A' = .70$) overall. Pairwise comparisons between means (Tukey test) confirmed that all groups differed from each other ($p < .05$). Because of group differences in PIQ (TD > [SLI = FL]), we wished to determine if group differences in grammatical sensitivity could be related to PIQ differences. To investigate for this possibility, we conducted an analysis of covariance (ANCOVA) with PIQ as the covariate. After controlling for PIQ differences, significant group differences in grammatical sensitivity remained $[F(2,67) = 12.931,\ p < .001]$.

A significant main effect for age $[F(2,69) = 10.543,\ p < .001]$ also was obtained and results revealed an increase in grammatical sensitivity with age. Pairwise comparisons between groups confirmed that the oldest children ($M\ A' = .86$) were more sensitive than the youngest age group ($M\ A' = .71$) to grammaticality ($p < .05$), with the middle age group of children ($M\ A' = .80$) falling in between. Notably, the group × age interaction was not significant. As can be seen in Tables 3–5 across age, we observe a similar pattern of grammatical sensitivity development for the TD, FL and SLI groups, despite overall sensitivity differences. At this level, results are compatible with a pattern of delay rather than deviance in both clinical groups.

There was a significant main effect of position $[F(1,69) = 15.593,\ p < .001]$, revealing that sensitivity was greater for violations occurring later ($M\ A' = .81$) compared to earlier in sentences ($M\ A' = .77$). This finding suggests that children were able to take advantage of the build-up of context across a sentence. The absence of significant interactions with age or group indicates that this processing advantage for late-placed violations develops early, and is apparent even at the different levels of accuracy/sensitivity observed in our two clinical populations.

A significant main effect of violation type $[F(2,138) = 21.585,\ p < .001]$ revealed that children were more sensitive to movement errors ($M\ A'\text{s} = .82$), least sensitive to substitution errors ($M\ A' = .77$), with sensitivity to omission errors falling in between ($M\ A'\text{s} = .79$). This pattern is consistent with previous studies of adult aphasic patients (Wulfeck, 1993; Wulfeck & Bates, 1991; Wulfeck et al., 1991a) and healthy adults under stressed processing conditions (Blackwell & Bates, 1995). It also indicates greater sensitivity to violations involving those cues that are most reliable in the participants' language. For speakers of English, the most reliable cues are those that involve word order or movement.

A significant interaction between position and violation $[F(2,138) = 9.795,\ p < .001]$ sheds further light on this pattern of differential sensitivity for violation type. As shown in Fig. 1, the pattern of vulnerability for substitution is greater for early violations. Hence build-up of context across a sentence increases listeners' sensitivity to the most difficult violation types. Movement violations are equally easy to detect whether they come early or late in a sentence, underscoring the importance word order cues (and violations of word order) in English.

Evidence for developmental change in grammatical processing patterns comes from two significant interactions: age by violation ($F(4,138) = 2.563,\ p < .05$), and group by age by violation $[F(8,138) = 2.027,\ p < .05]$. The age by violation effect (Fig. 2) shows a developmental shift in the relative difficulty of omission violations. For 7–8-year-olds, all of the violation types are challenging, although there is a slight disadvantage for agreement (substitution) errors (a harbinger of the profile for older children and adults). For 9–10 year olds, sensitivity to errors of movement has pulled ahead, with little difference between omission and substitution errors. By 11–12 years of age, children show greatest sensitivity to movement violations, least sensitivity to agreement violations, with omission violations falling in

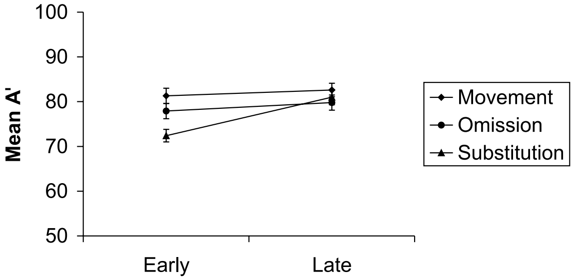

Fig. 1. Significant Position × Violation type interaction for A's.

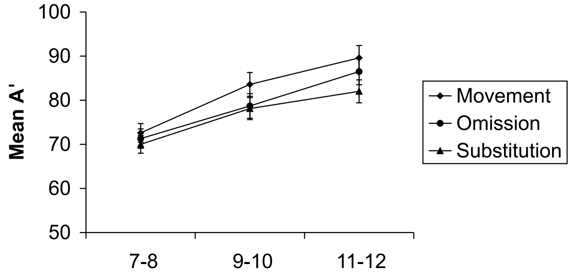

Fig. 2. Significant Age × Violation type interaction for A's.

between. In other words, the adult pattern is established by 11–12 years of age (Blackwell & Bates, 1995).

In order to better understand the nature of the significant three-way interaction of group, age and violation, we conducted separate within-group ANOVAS. In these analyses, the interaction of age and violation type was not significant for the TD and FL groups. That is, children in both groups were better at detecting movement than substitution violations, at every age. This pattern is consistent with findings for typical children (Wulfeck, 1993) and adults (Blackwell & Bates, 1995), and also observed in our FL group. This means that the three-way interaction is driven by the SLI group, who showed a significant age by violation interaction [$F(4,50) = 3.673$, $p < .05$]. Sensitivity to movement violations increased at a faster rate across age for the SLI groups (7–8-year-olds: $M\ A'\text{s} = .63$, 11–12-year-olds: $M\ A'\text{s} = .79$) compared to sensitivity to agreement errors (7–8-year-olds: $M\ A'\text{s} = .62$, 11–12 year olds: $M\ A'\text{s} = .71$). In other words, children with SLI are delayed across the board, but they are notably delayed in their ability to detect agreement violations.

Returning to the cross-population analyses, no overall effect of word class was obtained (i.e., no global difference between auxiliaries and determiners). However, significant interactions with position [$F(1,69) = 4.463$, $p < .05$], violation type [$F(2,138) = 4.645$, $p < .05$] and group [$F(2,69) = 3.903$, $p < .05$] were obtained. The interaction with position reflects two findings: (1) there were no sensitivity differences between auxiliaries or determiners when they were encountered early in sentences, but (2) there was a modest advantage for noun determiners ($M\ A' = .83$) compared to auxiliary verbs ($M\ A' = .80$) when they were encountered towards the end of sentences. The interaction with violation type can be explained as follows: (1) on movement violations, there is a sensitivity advantage for errors involving noun determiners ($M\ A' = .84$) compared to auxiliary verbs ($M\ A' = .79$) but (2) on violations of omission or substitution, there are no differences in sensitivity between auxiliaries and determiners. In other words, noun items are sometimes "easier" (and verb items are sometimes "harder"), but this difference is dependent on factors like type of error and position in the sentence.

The significant interaction between word class and group (Fig. 3) indicated the difference between auxiliary and determiner violations is coming primarily from the SLI group, who were less sensitive to auxiliary violations compared to determiner violations. This result is consistent with a body of evidence revealing that English-speaking children with SLI are especially impaired in verb morphology. The age by word class interaction just missed being significant ($p = .066$) with the youngest children showing "auxiliary disadvantage" observed in the SLI group overall. Hence the specific disadvantage for auxiliaries displayed by the SLI group may reflect developmental delay rather than deviance.

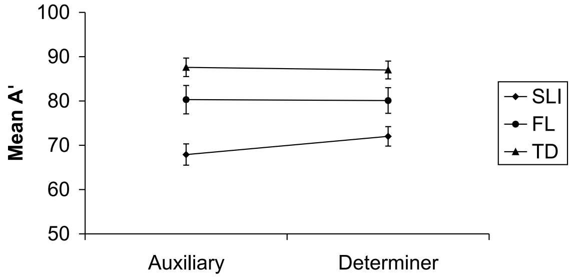

Fig. 3. Significant Word Class × Group interaction for A's.

3.2. Reaction time results

Baseline RT analyses revealed significant main effects for age [$F(2,69) = 14.865$, $p < .001$], but neither the main effect of group nor the interaction of group with age were significant. As expected, the age results revealed a developmental decrease in baseline RT (7–8 M RT = 990 ms; 9–10 M = 874 ms; 11–12 M = 748 ms).

Median RT values (with the child's mean baseline subtracted out) were computed for correctly rejected ungrammatical sentences for the 12 stimulus types for all groups (TD, FL, and SLI). These values were analyzed in a 3 (Group) × 3 (Age) × 2 (Position) × 2 (Word Class) × 3 (Violation) repeated measures analysis of variance (ANOVA). Reaction time (RT) analyses were conducted on the correctly rejected sentences only. For this reason, a child was not included in the RT analysis if there was complete failure by that child to identify ungrammatical sentences in one or more of the 12 stimulus cells. Upon inspection of each child's data, 5 TD, 6 FL (5 LHD and 1 RHD), and 11 SLI children were identified with missing cells and were excluded from the RT analyses reported here. In general, these children were from the two youngest age groups.

Age-related processing time differences were observed [$F(2,47) = 4.696$, $p < .05$]. Pairwise comparisons confirmed that the oldest children were faster (11–12-year-old M RT = 844 ms) compared to the 7–8-year-old children (M RT = 1334 ms), with performance by the 9–10-year-old group falling in between (M RT = 1147 ms). Recall that prior to analysis reaction times were adjusted by subtracting out a child's mean baseline RT from each response in order to control for developmental differences in motor skills. The observed age effect, although modest, indicates that even after adjusting for motor skills, developmental differences do exist in the time it takes children to detect violations. This pattern is consistent with greater sensitivity observed in older children. Since the RT analyses were conducted on correct responses only, it appears that when 7–8-year-old children detect grammatical violations, they are slower to process these compared to older children. The absence of a significant group effect or group by age interaction indicates that when violations are detected, overall processing speed is similar for all groups.

In the sensitivity analyses, we reported that children were more accurate at detecting violations that came at the end of sentences. The RT analyses reveal that children are also faster at judging sentences with later occurring (M RT = 507 ms) violations compared to early placed (M RT = 1710 ms) violations [$F(1,47) = 227.709$, $p < .001$]. This result replicates our previous work showing a word-position effect that we have interpreted as evidence that children, like adults, are capable of rapid word-by-word integration of information during sentence processing. The RT position effect finding suggests that the build-up of context may facilitate faster processing speed as well as sensitivity. A significant two-way position by age interaction [$F(2,47) = 5.235$, $p < .01$] shown in Fig. 4 indicates that developmental differences in the speed with which violations are detected are greatest for violations coming at the beginning of sentences. The position by group interaction was not significant, suggesting that there are similar processing advantages for late placed violations across groups, when violations are detected.

Although the main effect of violation type or interactions with age or group did not reach significance, the interaction of position and violation did [$F(2,94) = 7.028$, $p < .01$]. For violations that came early in sentences, slowest detection times were associated with omission violations (M RT = 1792 ms) compared to substitution (M RT = 1650 ms) and movement (M RT = 1686 ms) error detection. However, for those violations that occur at the end of a sentence, there is a timing advantage for omission (M RT = 399 ms) compared to movement (M RT = 628 ms) error detection with substitution error detection time (M RT = 494 ms) falling in between. These results are largely compatible with reports by Blackwell et al. (1996) on the time course of grammaticality judgments by adults. The absence of significant interactions of position and violation type with group suggests that these processing patterns operate even at the different levels of sensitivity noted for our study populations. To further explore processing related to error detection we turn next to findings for word class and interactions with other factors.

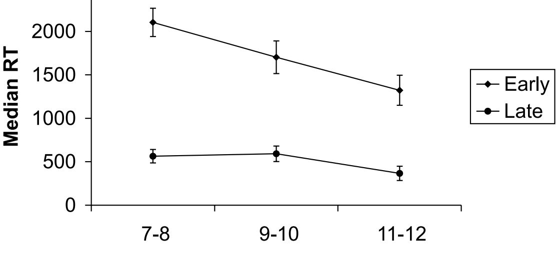

Fig. 4. Significant Position × Age interaction for median RTs.

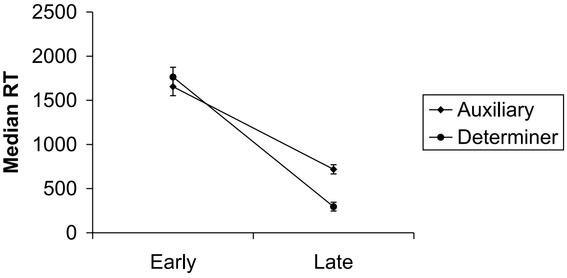

Fig. 5. Significant Word Class × Position interaction for median RTs.

The main effect of word class was significant [$F(1,47) = 13.688$, $p < .01$] as was the interaction of word class and position [$F(1,47) = 46.894$, $p < .001$]. Determiner violations (M RT = 1030 ms) were detected faster than auxiliary violations (M RT = 1187 ms). However, this difference comes from violations at the end of the sentence (Fig. 5) with a 423 ms processing advantage seen in the detection of determiner violations compared to agreement violations. This reaction time result (for correct rejections only) mirrors the effects for accuracy.

We underscore here that none of the interactions with group reached significance in these reaction time analyses. In other words, when children with FL or SLI are able to detect a grammatical error, they display the same reaction time profiles across error types and word class that we observe in typically developing children. However, it is important to keep in mind that not all children were included in the RT analyses, a topic to which we shall return.

4. Discussion

The purpose of this study was to examine grammatical sensitivity in typically developing children and in two clinical populations, children with early focal brain injury and children with specific language impairment. Linguistic (violation type, word class) and processing (word position of violation in sentences) manipulations were included. A real-time paradigm was employed so that processing times associated with violation detection also could be obtained. We have organized our discussion around the issues that motivated this study: (1) development of grammaticality sensitivity and processing; (2) vulnerability of grammatical processing in children with SLI; and (3) impact of early focal brain injury on grammatical processing.

4.1. The development of grammatical sensitivity and processing

School-age, typically developing children showed very good sensitivity to grammatical violations even when pressured to respond quickly. This result replicates our previous findings (Wulfeck, 1993), but now with a larger group of children, across a wider age range and with a new stimulus set. Grammatical sensitivity of the FL group, while below that of typically developing children, was well above chance, and also well above levels reported for adults with late onset lesions due to stroke (Wulfeck & Bates, 1991). The SLI group also showed above-chance performance, but their performance was well below the TD and FL groups and closer to profiles seen in aphasia.

Age effects were noted for all groups. In the absence of a significant group by age interaction, we must conclude that developmental patterns are similar within and across groups despite differing rates of grammatical sensitivity, however variability within the SLI group may have been a factor. Only the 11–12-year-old TD group showed grammatical sensitivity approaching levels reported for college-age subjects (Blackwell & Bates, 1995; Wulfeck et al., 1991a), indicating that grammatical sensitivity continues to develop through adolescence. In contrast, striking delays in grammatical sensitivity were seen across age for the SLI group. For example, overall performance by the oldest SLI group ($M\ A' = .75$) was closest to levels seen in the youngest TD ($M\ A' = .79$) and middle age FL groups ($M\ A' = .82$). As is common in the SLI population, individual differences were observed. For example, we examined A' scores of individual children for each of the 12 data cells and noted that half of the oldest children with SLI had most scores falling more than one standard deviation below the cell means of the youngest TD group. We did not observe this level of variability with the FL group. Taken together, these findings add to the existing literature revealing pronounced and persistent difficulties with grammar for children with SLI.

Despite overall differences in grammatical sensitivity, all groups across age were able to exploit the build-up of linguistic information across a sentence, as indicated by their greater sensitivity to and faster detection times for violations that occur late in the sentence. Since sentences varied in length, it is unlikely the effect is simply due to general "end of sentence" strategies. Instead, we attribute this effect to the ability to take advantage of intra-sentential structure. Interestingly, although we computed these RT analyses after adjusting for motor responses differences between children, we still obtained significant age and age by position effects. These findings suggest two things. First, improvement in processing efficiency continues with development, even with high levels of sensitivity seen in the youngest TD children. Second, age effects diminish when linguistic information accrues, towards the ends of sentences.

The absence of a significant group effect or group by age interaction for reaction time might appear somewhat surprising given, for example, evidence that children with SLI have limitations in information processing (Ellis Weismer, 1996; Kail, 1994; Leonard, 1998; Windsor & Hwang, 1999). However, it is important to keep in mind that in the present study, we limited our RT analyses to those responses associated with correct detection of ungrammatical sentences. As a result, one-third of the children from the SLI and FL groups and substantially fewer (18%) from the TD group were excluded from the RT analyses because of empty RT data cells. In general, the excluded children were from the youngest groups for whom we also observed lower sensitivity scores. We recognize, however, that by excluding these children from the RT analyses we lessen the possibility of detecting group RT differences. In studies currently underway, we are examining performance on two additional real-time language measures, complex sentence processing and past-tense production, and on untimed language production measures. Together with data from our judgment study, we are examining grammatical processing across tasks to see if individual or group profiles vary as a function of information processing demands.

In previous studies (Bates & MacWhinney, 1989; Wulfeck & Bates, 1991) we have noted that word order information is the most consistent cue to sentence comprehension in English, at each age level, within and across clinical groups. The sensitivity advantage for movement errors revealed in our study is compatible with the fact that English is a strong word order language with a weak inflectional morphology system. Children may notice movement violations more easily because word order is a powerful cue that develops early compared to rules of agreement that are acquired later by typical children and consistently more difficult for children with SLI.

On the other hand, there are also reasons to believe that agreement information is especially vulnerable for aphasic patients in many different languages (Bates & Wulfeck, 1989; Bates, Wulfeck, & MacWhinney, 1991). In the Wulfeck et al. (1991a) study, agreement errors were more difficult to detect than movement errors for Italians as well as English language patients although the magnitude of this "agreement disadvantage" varied with language (greater for English, smaller for Italian). Furthermore, studies of typical adults under stress in German (Dick, Bates, Ferstl, & Friederici, 1999a; Kilborn, 1991) and Italian (Bates et al., 1994) yielded results similar to those for English (Blackwell & Bates, 1995), indicating that agreement information is especially vulnerable under adverse processing conditions, including perceptual degradation and dual task conditions. In line with Blackwell and Bates, we suggest that substitution errors may also be harder to detect because they are less salient in English. Movement errors may be especially easy to detect because they have two cues that point to ungrammaticality. First, a hole is created by removing the target element and then that element is moved to another part of the sentence where it disrupts grammaticality further. In other words, more information is available to child and adult listeners, drawing their attention to movement violations.

We want to underscore that accuracy and reaction time measures do not always yield the same results. Children were less sensitive to agreement violations, but these violations did not take longer to detect. In fact, correct detection of agreement violations tended to be especially fast for our child participants. This result for children is consistent with the time-course studies of typical adults by Blackwell et al. (1996). Omission and movement errors take longer to detect because (at least for a very short time) the sentence looks as though it could be "salvaged." This is not true for agreement errors: when they are wrong, they are wrong right away. This is one more example in which children in our study show on-line processes similar to those observed in adults, albeit at slower speeds and lower levels of accuracy.

4.2. *The vulnerability of grammatical processing in children with SLI*

Several findings provide evidence for the vulnerability of grammatical processing in SLI, compared with the TD and FL groups. First, overall performance by the SLI group was impaired with respect to typical children. This was of course what we would expect given how SLI is defined. However, results also reveal a disadvantage compared to children in the FL group. This result suggests that underlying pathology responsible for SLI may be more pervasive and less plastic than the focal pathology for children with FL (Trauner, Wulfeck, Tallal, & Hesselink, 2000).

Second, significant delays in grammatical processing were observed for SLI children in our cross-sectional study, with the oldest children showing sensitivity levels below those of typical children three to five years younger. Third, although the SLI group showed a pattern of sensitivity to word order violations similar to that of the TD and FL groups, they were the only group who showed an interaction of age and violation type. This result indicates a more protracted developmental trajectory for detection of agreement violations, similar to patterns of sensitivity observed for adults with aphasia (Wulfeck & Bates, 1991; Wulfeck et al., 1991a) and healthy adults under adverse conditions (perceptual degradation; memory load).

Finally, children with SLI displayed a selective disadvantage for auxiliaries compared to determiners. This difference did not reach significance for the TD or FL groups. However, a parallel finding that auxiliaries were generally harder for younger children ($p < .066$) suggests that the "auxiliary disadvantage" may constitute one more example of delay rather than deviance in the SLI profile. Our results confirm differential problems consistent with previous reports of grammatical difficulties for children with SLI, whereas the RT analyses indicate that when these children notice violations, their performance is similar overall to typical children and children with FL.

4.2.1. *The impact of early focal brain injury on grammatical processing*

Our results add to the literature showing neural and behavioral plasticity in children with early unilateral brain injuries (Bates & Roe, 2001; Bates et al., 1999; MacWhinney et al., 2000; Stiles, Bates, Thal, Trauner, & Reilly, 1998). Also, no effect of lesion side was observed (i.e., no difference between children with left- vs. right-hemisphere damage). Furthermore, although the FL children as a group performed below typical children, they displayed significantly better performance than children with SLI. These results are strikingly similar to reports for the three populations (FL, SLI, and TD) in other studies from our group (see this issue). The fact that we have found the same pattern for on-line grammaticality judgment (a challenging task even for adults) illustrates the degree of recovery and compensatory organization that is possible for children with early focal brain lesions despite initial delays in language development.

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