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Research Article

Cognitive Functions in Childhood Apraxia of Speech

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Purpose: Childhood apraxia of speech (CAS) is diagnosed on the basis of specific speech characteristics, in the absence of problems in hearing, intelligence, and language comprehension. This does not preclude the possibility that children with this speech disorder might demonstrate additional problems.
Method: Cognitive functions were investigated in 3 domains: complex sensorimotor and sequential memory functions, simple sensorimotor functions, and nonrelated control functions. Seventeen children with CAS were compared with 17 children with normal speech development at 2 occasions within 15 months.
Results: The children with CAS showed overall lower scores but similar improvement at Occasion 2 compared with the typically developing controls, indicating an overall delay in the development of cognitive functions. However, a specific deviant development in sequential abilities was found as well, indicated by significantly lower scores at Occasion 2 as compared with younger control children at Occasion 1. Furthermore, the scores on the complex sensorimotor and sequential memory tasks were significantly correlated with the severity of the speech impairment.
Conclusions: These results suggest that CAS involves a symptom complex that not only comprises errors of sequencing speech movements but implicates comorbidity in nonverbal sequential functioning in most children with CAS.

Childhood apraxia of speech (CAS) has been associated with a wide variety of diagnostic descriptions and has been shown to involve different symptoms during successive stages of development (Maassen, 2002; Maassen, Nijland, & Terband, 2010). Dispute continues about the clinical characteristics and the precise origin of CAS, but researchers and clinicians do agree that it is primarily a motor–speech disorder with a core deficit in planning and/or programming the spatiotemporal parameters of movement sequences (American Speech-Language-Hearing Association [ASHA], 2007; Hall, Jordan, & Robin, 2007; Maassen et al., 2010; Shriberg, 2010). Although ASHA (2007) stated that "there presently is no one validated list of diagnostic features of CAS that differentiates this disorder from other types of childhood speech sound disorders, including those apparently due to phonological level deficits or neuromuscular disorder (dysarthria)" (p. 5), some agreement has been established about a core set of speech–motor symptoms. One of the most prominent speech characteristic is inconsistent errors on consonants and vowels in repeated productions of syllables or words (ASHA, 2007; Hall et al., 2007; Ozanne, 2005). The errors are not typically immature and mainly comprise a large number of consonantal errors in which omissions are more prevalent than substitutions. The vowel errors are mostly distorted productions and vowel reductions. Often, the errors constitute nonphonemic productions that defy accurate transcription, even when using narrow transcription. A second prominent symptom of CAS is deviant or disrupted coarticulatory transitions between sounds and syllables (ASHA, 2007; Hall et al., 2007; Ozanne, 2005). Coarticulation in the speech of children with CAS as compared with typically developing children has been found to be both stronger and more extended as well as the opposite: more segmental (or hyperarticulated; Nijland et al., 2002, 2003). Further important features of the speech of children with CAS include groping or searching articulatory behavior (both prevocalic and during sound production) and difficulties with and low maximum repetition rates in the production of alternate

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syllables or diadochokinesis (ASHA, 2007; Hall et al., 2007; Ozanne, 2005).

There are several arguments to broaden the perspective of research on CAS to other developmental domains. The first is that speech normally develops in interaction with other psycholinguistic and cognitive functions (Locke, 1994), and the speech of a child with CAS may show different manifestations and clinical characteristics during speech development (Maassen, 2002; Maassen et al., 2010). Not only are speech–motor and phonological skills closely related, but other functions such as verbal short-term memory, attention, and general motor planning skills show interactions with speech functions. For example, it has been shown that efficiency of speech coding influences verbal short-term memory and that short-term auditory memory is a prerequisite for speech (e.g., Bishop, 1997). In addition, deficits in the storage and retrieval of speech representations, besides those in planning/programming and representational encoding, have been shown in children with CAS (Shriberg, Lohmeier, Strand, & Jakielski, 2012), and a recent series of studies has found that in several multigenerational families with a history of CAS, the affected members show a central deficit in sequential processing[1] (Button, Peter, Stoel-Gammon, & Raskind, 2013; Peter, Button, Stoel-Gammon, Chapman, & Raskind, 2013; Peter, Matsushita, & Raskind, 2012; Peter & Raskind, 2011). A second argument to look beyond speech functions in studies of CAS is the growing body of neurobehavioral and neurophysiological evidence that "cognition exerts strong influences on motor control, such that speech, or any motor behavior, is best viewed as a cognitive-motor accomplishment" (Kent, 2004, p. 3).

In the present study, we followed this line of research to go beyond speech motor functions and investigated other perceptuo-motor and cognitive functions in children with CAS, both directly related as well as unrelated to speech. Apart from providing more indications with regard to the underlying deficit of the disorder, the results contribute to the discussion of whether CAS can be viewed as a separate entity or unitary disorder with associated problems (comorbidity) or as a symptom complex arising from a diversity of underlying deficits (consistently present but variable in severity across individuals; Shriberg, Aram, & Kwiatkowski, 1997; Shriberg et al., 2012). Before discussing the design of the present study, we first give an overview of neuropsychological studies of CAS.

Cognitive Functions in CAS

Although the disorder CAS is defined by its speech characteristics, most children with CAS also show impairments in other linguistic and nonverbal functions (e.g., Davis, Jakielski, & Marquardt, 1998; McCabe, Rosenthal, & McLeod, 1998; Newmeyer et al., 2007; Nijland, 2009; Teverovsky, Bickel, & Feldman, 2009). Also, "soft" neurological signs such as motor coordination deficits (clumsiness) and mild motor retardation have been mentioned in the literature (e.g., Ferry, Hall, & Hicks, 1975; McCabe et al., 1998; Newmeyer et al., 2007; Velleman & Strand, 1994). Teverovsky et al. (2009) assessed a wide range of general functional characteristics of 192 children with CAS through a parent/caretaker survey. Problems regarding attention, vestibular, and fine motor functions were reported in about 50% of the cases. However, little has been published about neuropsychological behavioral research concerning children with CAS. For example, attention, which is a commonly studied function in developmental disorders, has not been studied directly in children with CAS. The few studies that do not deal with speech and language characteristics have mainly focused on motor behavior, memory capacity (in particular, sequential memory), and sensory processing (an overview of each is provided in the next three subsections). The results of these studies and their interpretations diverge.

Motor Functioning

Whereas some studies suggested that the difficulties in programming sequences of movements in CAS are restricted to the articulators (verbal and oral tasks; e.g., Aram & Horwitz, 1983), other studies assumed a motor sequencing disorder in CAS that is also found in limb movements (Yoss & Darley, 1974), and some even suggested a more generalized motor disorder in simple and complex movements (Bradford & Dodd, 1996; Dewey, Roy, Square-Storer, & Hayden, 1988; Williams & Bishop, 1992).

According to Dewey et al. (1988), children with CAS have trouble with transitions between different movements within one motor sequence (e.g., pulling a knob and then turning it around) but not with repetition of the same movement a few times (as in finger tapping). Thus, motor difficulties in children with CAS might be restricted to complex or sequential motor behavior. In line with these findings, Bradford and Dodd (1996) found that children with CAS scored low on both fine motor tasks and sequential oral motor movements, compared with children with other speech disorders and with control children. They interpreted these results as a deficit at the level of integrating sensory information into a plan of action (which is also a common explanation used in explaining limb apraxia; De Renzi, Faglioni, & Sorgato, 1982) and at the level of coordinating the speed and dexterity of complex movements. In line with this notion of CAS as a global deficit in motor sequencing, a series of studies by Peter and colleagues that investigated several multigenerational families with a history of speech difficulties consistent with CAS reported slower speeds during alternating as compared with repetitive sequential motor tasks in both articulatory and finger movements (Button et al., 2013; Peter et al., 2013; Peter & Raskind 2011).

[1] *Sequential processing* in this study refers to the order of elements of the motor performance rather than the smooth transitions between movements.

Memory

Several studies investigated memory capacity in diverse populations of children with phonological disorder and specific language impairment, but only a few studies have been reported on memory capacities in CAS specifically. The results in these few studies, as in studies on motor behavior, are rather diverse. Dewey et al. (1988) showed that spatial memory and memory for sequences were poorer in children with CAS. However, they concluded that these memory deficits were not related to difficulties with motor sequencing. Raine, Hulme, Chadderton, and Bailey (1991) made a different suggestion about the relation between memory and sequencing. They interpreted the lower short-term memory capacity in speech-disordered children to be causally related to slow speech rate. This view was also supported by Hulme and Roodenrys (1995), who suggested that the development of verbal short-term memory skills seems to be intimately related to the development of speech production (and speech perception) mechanisms. Thus, short-term memory deficits have been reported in studies on speech disorders as well as language disorders, which questions the specificity of the relationship between short-term memory deficits and CAS.

Sensory Processing

Problems in orosensory feedback have been mentioned occasionally as symptom of CAS (McCabe et al., 1998), and a reduced or degraded oral sensitivity has been proposed in the literature as a possible core deficit of CAS (Terband & Maassen, 2010; Terband, Maassen, Guenther, & Brumberg, 2009). Newmeyer and colleagues (2009) investigated sensory processing in 38 children with severe CAS using the Sensory Profile (Dunn, 1999), a standardized parent/caretaker questionnaire that measures children's ability to process sensory information and provides a profile of the effect of sensory processing on their performance in everyday tasks. The results indicated differences in sensory processing in the children with CAS in addition to speech impairment in five factor clusters including sensory seeking, emotional reactiveness, oral sensory sensitivity, inattention/distractibility, and fine motor/perceptual skills, suggesting that children with CAS may respond in a passive way to sensory input. Furthermore, the results showed a positive correlation between the severity of the apraxia and the sensory sensitivity quadrant score (which is thought to represent low neurological thresholds with a passive self-regulation strategy; Dunn, 2006).

With respect to auditory processing, a large body of neuropsychological data is available, and several studies have found subtle (subclinical) auditory processing deficits in children with CAS (Bridgeman & Snowling, 1988; Groenen, Maassen, Crul, & Thoonen, 1996; Hodge, 1994; Love & Fitzgerald, 1984; Maassen, Groenen, & Crul, 2003; Nijland, 2009; Stackhouse & Snowling, 1992; Yoss & Darley, 1974). Compared with typically developing controls, children with CAS have been found to show poorer auditory discrimination of consonants (Groenen et al., 1996; Raaymakers & Crul, 1988) and vowels (Maassen et al., 2003) as well as poorer performance on nonword discrimination and word rhyming tasks (Nijland, 2009).

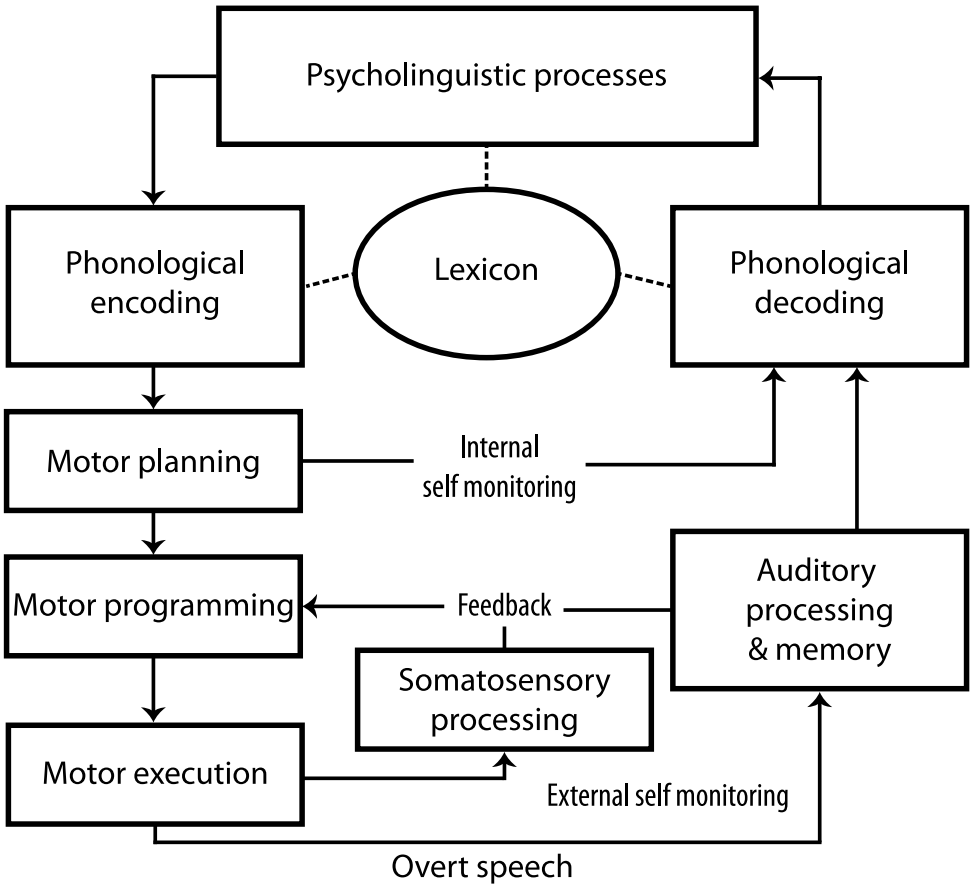
Aims of the Study

To summarize, although dysfunctions in addition to the speech problems in CAS have been mentioned in the literature, the research results are limited and, where available, rather divergent and difficult to compare due to differences in tasks and selection criteria. In the present study, we investigated whether children with CAS show different (i.e., lower) scores compared with typically developing children on a broad spectrum of cognitive functions, both directly related as well as unrelated to speech. We used stringent selection criteria to select children who have clear cases of CAS without additional problems in hearing, language comprehension, gross motor functioning, and intelligence. Furthermore, the children were tested on two occasions, 15 months apart, which enables us to discuss the issue of deviance versus delay in development (e.g., Frith, 1985).

In order to choose the cognitive functions that might be of interest in children with CAS, we took processes of speech production and perception as a starting point. Figure 1, based on Levelt and colleagues (Levelt, 1989; Levelt, Roelofs, & Meyer, 1999), displays the sensorimotor and memory functions involved in speech processing. According to this model, speech is driven by the word forms retrieved from the lexicon. These word forms go into a stage of phonological encoding to select and sequence the auditory–motor targets that constitute the speech sounds, followed by motor planning (selection) and programming (implementation, parameterization) the articulatory movements. The thus-constructed motor plan is executed during the motor execution phase, resulting in the actual movements of the articulators. An important aspect of the model for the present study, apart from this succession of stages, is the use of internal and external feedback. Internal feedback is used for self-monitoring, so that, for instance, erroneously planned speech movements are not executed. These "covert repairs" play a role in theories of stuttering (Postma & Kolk, 1993). During motor execution, both fast somatosensory and slow auditory monitoring takes place, possibly resulting in corrections of programming and execution.

For the present study, this model was used to construct analogous nonspeech tasks, presented in Table 1. The analogous nonspeech tasks can be divided into two groups: those that require sequencing (order of movements and smooth transitions, as determined during motor planning) and those that are primarily related to force and speed of movement and sensory integration (as determined during motor programming and execution). As outlined herein, CAS is described as a specific impairment in speech motor planning and/or programming (ASHA, 2007; Hall et al., 2007; Maassen et al., 2010; Shriberg, 2010). In the present study we investigated the auditory, memory, and sensorimotor functions of children with CAS in both the

Figure 1. Model of speech processing. Figure based on Levelt and colleagues (Levelt, 1989; Levelt, Roelofs, & Meyer, 1999).



domain of speech processing as well as other motor and memory tasks. The aim of the study is to determine to what extent children with CAS show deficits in the analogous nonspeech processes. Clinically, such deficits might provide evidence of comorbidity.

The functions that were examined in this study can broadly be divided into three domains: complex sensorimotor and sequential memory functions, simple sensorimotor functions, and control functions (not presented in Table 1). If children with CAS have an underlying deficit in sequencing that is not restricted to speech and speech movements, we expect the children with CAS to experience problems in nonspeech complex sensorimotor and sequential memory tasks. To test for specificity, sequential and nonsequential memory functions were compared. Whether also simple sensorimotor tasks consisting of motor execution and sensory processing could be related to CAS is questioned in the literature. In the present study we compared complex and simple manual tasks. As control functions, generally assumed not to be related to CAS, attention, spatial memory (in contrast with

Table 1. Stages of speech production with analogous nonspeech tasks.

Stage of speech production	Function	Speech errors	Analogous nonspeech tasks
Phonological encoding	Specify and sequence abstract targets (phonemes) in context	Anticipations, perseverations, transpositions of speech sounds	Auditory rhythm; hand movements; number recall; word order
Motor planning [= phonetic planning][a]	Hierarchy (syllables; prosody) and order of speech movements; transitions	Prosodic errors; word- and syllable-structure errors; inconsistency; slow transitions	
Motor programming and execution[a]	Parameterization (speed and force)	Distortions; slow speech	Finger tapping; oral sensory;[a] finger localization[a]

[a]Including self-monitoring.

sequential memory), and planning (a more cognitive executive function) were considered. The relation between cognitive functions and speech functions was determined directly by calculating correlations between the severity of dysfunction in both domains.

Method

Participants

Two groups participated in this study: a group of children with CAS and a group of typically developing children. To come to a thorough selection of the children with CAS, the following procedure was conducted. First, speech therapists at special schools for children with speech and language disorders selected children in the age range of 4 to 7 years; criteria were specific speech difficulties and a clinical judgment of suspected CAS. The speech therapists also filled in a form concerning speech characteristics of these children. Seventy children were referred for further assessment. Subsequently, recordings were made of these children, and these were judged by the authors and assistants who were speech-language pathologists (consensus judgment) on intelligibility of speech and the possible involvement of dysarthria; in addition, the criteria described in Hall et al. (2007) and Thoonen, Maassen, Wit, Gabreëls, and Schreuder (1996) were applied in order to select the clear cases of CAS. First, clinical judgments of poor intelligibility of spontaneous speech and the presence of groping and inconsistent speech errors were applied to select children with suspected CAS. To verify the diagnosis, quantitative characteristics were assessed, namely, a high rate of consonant substitutions, especially with respect to place of articulation, and relatively poor performance on the trisyllabic maximum repetition rate task (/pataka/) as compared with the monosyllabic maximum repetition rate tasks (/papapa . . . /, /tatata . . . /, /kakaka . . . /). For details, see Appendix A. In addition, exclusion criteria were below normal intelligence (IQ more than 1 *SD* below average), hearing problems (pure-tone thresholds at frequencies from 250 to 8000 Hz above 25 dB HL),[2] problems with language comprehension (scores of more than 1 *SD* below average on the Reynell Test–Second Edition, Reynell & Huntley, 1985; see Appendix A), structural disorders in the orofacial area, gross motor disturbances, and dysarthria. Of the 70 referred children, 19 (14 boys, five girls) were selected as having clear cases of CAS. A second group consisted of typically developing children, matched for (average) age, gender, and dialect region.

Procedure

Neuropsychological data were collected twice in a period of about 1–1.5 years (mean interval = 15 months) for 17 of these children with CAS[3] and 17 typically developing children (see Appendix A for descriptive data of both groups of children). It was assumed that this period of 15 months was long enough to show a significant effect of development in the typically developing children and to show a possible difference in development between the two groups. The age of the children with CAS at Occasion 1 was between ages 4;11 [years;months] and 6;10 (M = 5;8); the typically developing children were slightly younger: between 4;7 and 6;6 (M = 5;6). The age of the children with CAS at Occasion 2 (about 15 months later) was between 6;1 and 8;3 (M = 6;11); the typically developing children were between the age of 6;3 and 8;0 (M = 7;1).

Test Materials

Ten subtests were selected in three areas: (a) complex sensorimotor and sequential memory tasks, (b) simple sensorimotor tasks, and (c) control tasks. Five of the 10 subtests were derived from standardized assessment batteries: the Kaufman Assessment Battery for Children (K-ABC; Kaufman & Kaufman, 1983) and the Revised Amsterdam Children's Intelligence Test (RAKIT; Bleichrodt, Drenth, Zaal, & Resing, 1984), for which age norms are available. The other five subtests did not have normalized scores (for detailed description of each subtest, see Appendix B). Because a comparison group of age-matched typically developing children was available in this study, we only report non-normalized scores in the analyses. Furthermore, hand preference of each child was determined on the basis of the hand that was used for writing/drawing. The tests are summarized in Table 2 and fully described in Appendix B.

Statistical Analysis

Before the statistical analyses were performed, the scores of the left hand and right hand were transposed according to hand preference. This means that the scores of the right hand were transposed to preference-hand scores in case of a right-handed child and to nonpreference-hand scores in case of a left-handed child, and vice versa for the left-hand scores.

In order to test whether the two groups differed and whether this changed over time, analyses of variance were performed with Occasion (levels: Occasion 1, Occasion 2) as the within-subject factor and Group (CAS, typically developing) as the between-subjects factor (Winer, Brown, & Michels, 1991). The main effects of Group and Occasion were determined as well as the effect of the Group × Occasion interaction. A multivariate analysis of variance was conducted to investigate the main function domains (complex and simple sensorimotor functions; control functions), and subsequent univariate analyses of variance were conducted on the separate variables.

In order to evaluate whether children with CAS show a deviance in development rather than just a delay, we compared the results of Occasion 2 of children with CAS with the results of Occasion 1 of the typically developing children. For this, analyses of variance were performed on the nonnormalized (for age) scores.

[2]All children were tested on hearing and intelligence at their schools.
[3]Neuropsychological data of two children at Occasion 2 were not complete and therefore were excluded from further analyses.

Table 2. Overview of the subtests (and the assessment battery from which each is derived).

Function	Description	Assessment battery
1. Complex sensorimotor & sequential memory tasks		
a. Auditory rhythm	Tap an auditory ± visually presented rhythm with one or both hands.	Similar to Peter & Stoel-Gammon (2005; no age norms)
b. Hand movements	Imitate a sequence of hand movements.	K-ABC
c. Number recall	Imitate a sequence of digits verbally.	K-ABC
d. Word order	Sequentially point to pictures of verbally presented words for objects.	K-ABC
2. Simple sensory-motor tasks		
e. Finger tapping	Tap as fast as possible for 10 s with left and right index fingers.	PINOK (Vieijra, König, Gardien, & de Vries, 1994; no age norms)
f. Oral sensory	Identify three-dimensional objects orosensorily.	Similar to Rosenbek, Wertz, & Darley (1973; no age norms)
g. Finger localization	Identify fingers touched by experimenter (verbal or by pointing at picture of hand); one or two fingers touched.	Described in (Benton, Hamsher, Varney, & Spreen, 1983; no age norms)
3. Control tasks		
h. Labyrinths	Go through a labyrinth with a pencil (visual–motor integration task).	RAKIT
i. Spatial memory	Point to the location of pictures after disappearance.	K-ABC
j. Attention	Cross out pictures of pears among apples.	Konzentrationstest für das erste Schuljahr (Möhling & Raatz, 1974; no age norms)

Note. K-ABC = Kaufman Assessment Battery for Children (Kaufman & Kaufman, 1983); PINOK = Peadologisch Instituut Neuropsychologisch Onderzoek bij Kinderen; RAKIT = Revised Amsterdam Children's Intelligence Test (Bleichrodt et al., 1984).

A Bonferroni correction to adjust for multiple statistical tests was not applied because this creates an unacceptably high probability of making a Type II error in analyses with small group sizes (Nakagawa, 2004). Rather, multiple comparisons are accounted for in the interpretation of the results (Rothman, 1990).

The relation between variables was tested using factor analyses for each occasion separately (to answer the question of which subtests are significantly related to each other). Principal component analyses were conducted, and factors with eigenvalues of 1 or greater were retained. Additionally, varimax orthogonal rotation with Kaiser normalization was used to enhance interpretability. To evaluate the reliability of the factor analyses, we performed a series of analyses to check whether sample size and the correlations between variables were adequate. Sampling adequacy was verified by investigating factor loadings, the variables' communalities, and by the Kaiser–Meyer–Olkin (KMO) measure of sampling adequacy. Adequacy of correlations was verified by investigating the correlation matrix and by Bartlett's test of sphericity (Field, 2013).

Subsequently, correlations (Pearson's r) were determined between the factor scores of the two factors and speech data obtained during the first recording session. Given that the speech measures are not mutually independent, it can be argued that a Bonferroni correction to adjust for multiple statistical tests is not appropriate. In addition, as explicated above, it has been shown that in analyses with small group sizes, a Bonferroni correction creates an unacceptably high probability of making a Type II error (Nakagawa, 2004). Therefore, we decided not to apply a Bonferroni correction and to take multiple comparisons into account in the interpretation of the results.

Results

Children With CAS Versus Typically Developing Children

Table 3 displays the mean scores of Occasion 1 and Occasion 2 for both groups of children. The table clearly shows that children with CAS have overall lower scores than the typically developing children. Furthermore, overall the values at Occasion 2 were higher as compared with Occasion 1 for both groups.

Before conducting parametric analyses, the assumption of normality was tested using Kolmogorov–Smirnov (K-S) tests for each variable on the nonnormalized (for age) scores. The results of this test showed that the scores of all variables were normally distributed (all K-S Z scores < 1.33; nonsignificant), except for three variables that had a strong ceiling or bottom effect. A bottom effect was found in auditory rhythm–both hands at Occasion 1 of children with CAS (K-S $Z = 1.63$, $p < .01$) and attention: omissions at Occasion 2 of typically developing children (K-S $Z = 1.43$, $p < .05$); a ceiling effect was found for finger localization: one finger with looking at both occasions of typically developing children (Occasion 1: K-S $Z = 1.38$, $p < .05$; Occasion 2: K-S $Z = 1.52$, $p < .05$). Therefore, the effects of Occasion and Group were tested on composite scores (totals) of auditory rhythm (preference hand, nonpreference hand, both hands) and finger localization: one finger ("with looking" was added to "without looking"). These composite scores were normally distributed (all K-S Z scores < 1.00; nonsignificant).

Subsequently, analyses of variance were used to test the significance of the effects of Group and Occasion and the Group × Occasion interaction. The results of the analyses of variance are displayed in Table 4.

Table 3. Nonnormalized test scores (mean and standard deviation) of the children with childhood apraxia of speech (CAS) and the typically developing children at the two occasions.

	Children with CAS				Typically developing children			
	Occasion 1		Occasion 2		Occasion 1		Occasion 2	
Variables	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
1. Complex sensorimotor and sequential memory								
Auditory rhythm–preference hand	1.6	1.6	2.7	3.1	7.5	2.4	7.5	2.7
Auditory rhythm–nonpreference hand	1.1	1.2	2.5	2.1	7.2	2.5	6.4	3.3
Auditory rhythm–both hands	0.5[b]	1.1	1.8	1.6	5.4	2.9	8.2	5.0
Hand movements	6.7	2.2	8.8	3.3	10.5	2.4	12.4	3.5
Number recall	5.1	1.6	7.1	1.5	9.1	1.7	11.4	2.1
Word order	6.1	1.4	6.8	1.9	10.0	2.9	11.5	3.6
2. Simple sensorimotor								
Finger tapping–preference hand	23.9	4.7	25.2	3.7	27.9	3.5	31.4	3.2
Finger tapping–nonpreference hand	21.0	3.6	24.2	5.2	25.5	2.8	27.8	4.4
Oral sensory	5.5	1.6	5.8	1.6	6.7	1.0	6.8	1.0
Finger localization: 1 finger with looking	16.9	4.0	18.1	2.4	18.9[a]	1.6	19.5[a]	0.8
Finger localization: 1 finger without looking	8.4	4.3	13.6	3.9	15.1	2.4	17.1	2.3
Finger localization: 2 fingers without looking	2.1	2.0	6.8	3.1	9.1	3.7	11.1	3.5
3. Control tasks								
Labyrinths	50.9	11.1	68.5	10.6	54.7	10.0	73.7	7.2
Spatial memory	5.3	3.5	10.2	3.8	9.9	3.2	12.4	2.7
Attention: mean row time	12.1	3.6	8.1	2.2	8.9	2.9	6.4	1.5
Attention: omission	6.4	4.0	1.9	2.3	2.7	2.5	1.1[b]	1.9

[a]Indicates no normal distribution of the data due to a ceiling effect. [b]Indicates no normal distribution of the data due to a bottom effect.

The results of the multivariate analyses showed significant effects of both Group and Occasion on all domains, but no effect of the Group × Occasion interaction. This indicates that the scores of the children with CAS were lower than those of the typically developing children in all three domains and on both occasions and that both groups had higher scores at Occasion 2 than at Occasion 1.

When considering the results of the univariate analyses of variance, we can observe slight differences. No significant effect of Group was found in the labyrinths variable, which means that the children with CAS did not have significantly lower scores than the typically developing children at either occasion. Furthermore, the variables auditory rhythm, word order, and oral sensory showed a significant effect of Group but not of Occasion. This indicates that although children with CAS scored lower than typically developing children on these tasks, no significant change was found at Occasion 2 as compared with Occasion 1. However, auditory rhythm showed an additional effect of the Group × Occasion interaction, showing that the improvement in typically developing children at Occasion 2 was larger than in the children with CAS, especially in the

Table 4. Results of the analyses of variance with between-subjects factor Group and within-subject factor Occasion.

		Group		Occasion		Group × Occasion	
Variable	*df*s	*F*	η^2	*F*	η^2	*F*	η^2
Multivariate–complex sensorimotor & sequential memory tasks	4, 28	18.64***	.73	18.64***	.72	1.29	.16
Auditory rhythm total score	1, 31	53.87***	.64	1.18	.4	4.32*	.12
Hand movements	1, 31	18.09***	.37	13.73**	.31	0.08	.003
Number recall	1, 31	58.43***	.65	70.34***	.69	0.30	.01
Word order	1, 31	37.16***	.55	3.78	.11	0.44	.01
Multivariate—simple sensorimotor tasks	4, 27	15.59***	.70	11.30***	.63	1.55	.19
Finger tapping	1, 30	13.24***	.31	24.71***	.45	0.27	.01
Oral sensory	1, 30	8.76**	.23	1.65	.05	0.67	.02
Finger localization–1 finger	1, 30	26.10***	.47	18.28***	.38	4.54*	.13
Finger localization–2 fingers without looking	1, 30	51.19***	.63	18.08***	.38	3.32	.10
Multivariate—control tasks	3, 30	5.62**	.36	46.57***	.82	2.66	.21
Labyrinths	1, 32	2.43	.07	114.72***	.78	0.17	.01
Spatial memory	1, 32	10.85**	.25	60.50***	.65	7.16*	.18
Attention: mean row time	1, 32	10.27**	.24	44.17***	.58	2.34	.07

Note. Multivariate F ratios are generated from Wilks's lambda.

*$p < .05$. **$p < .01$. ***$p < .001$. Multivariate *F* ratios are generated from Wilks's lambda.

bimanual task. Finally, a Group × Occasion interaction effect was also found for finger localization: one finger and spatial memory. This was due to a larger increase across occasions in children with CAS as compared with typically developing children. Post hoc analysis of the scores at Occasion 2 still showed a significant difference between groups on finger localization, $t(32) = 3.42$, $p < .01$. In contrast, post hoc analyses on spatial memory did not show a significant difference between the typically developing children and the children with CAS at Occasion 2, $t(32) = 1.88$ (nonsignificant). This indicates that the children with CAS caught up with the typically developing children on the spatial memory task.

To summarize these data, the children with CAS had significantly poorer results than the typically developing children. Although overall the scores improved at Occasion 2, the difference between the two groups continued to exist, except for the scores on spatial memory, which were no longer lower in children with CAS. The main result was that the differences between CAS and controls increased on the auditory rhythm tasks, in that typically developing children showed a larger improvement at Occasion 2 than children with CAS. This is explicated in the next section.

CAS: Deviant, or Delayed Development?

The fact that all children (the control subjects as well as the children with CAS) showed a similar improvement at Occasion 2 and the children with CAS caught up with the typically developing children on spatial memory at Occasion 2 led us to additionally analyze the results in a different way. Could it be the children with CAS simply go through a delayed development rather than a deviant development? In order to evaluate this issue, the results of the children with CAS at Occasion 2 were compared with the results at Occasion 1 of the typically developing children. Results of the analysis of variance are shown in Table 5. From the results presented in Tables 3 and 5, we may conclude that the children with CAS in comparison with younger typically developing children perform equally on nonrelated functions (the control tasks) and the simple sensorimotor functions (except for the labyrinths task; on this task the children with CAS scored better than the younger controls) but still had lower scores on the complex sensorimotor and sequential memory functions (except for the hand movements task, which did not reach significance). Thus, the cognitive functions of children with CAS do not show a harmonic profile: Whereas some functions show a delay in development, others (complex sensorimotor and sequential memory functions) are more likely to be deviant. In addition, the significant multivariate group difference of the control tasks is due to the average score of the control task labyrinths being significantly higher in children with CAS as compared with (younger) typically developing children.

Relations Between Variables

Factor analyses were conducted to test which functions were highly related to each other. Interitem product–moment correlation coefficients were calculated, and principal component analyses were conducted for both occasions separately. To reduce the number of variables entered into the analysis, finger localization: one finger and finger localization: two fingers without looking were substituted by the combined score on the total finger localization task.

The analyses resulted in two factors at each occasion. To evaluate the reliability of the factor solutions, we performed a series of analyses to verify whether sample size and correlations between variables had been adequate. Following Field (2013), sampling adequacy was verified by investigating the factor loadings and the variables' communalities. Given that both factors contain at least four loadings of .6 or higher and that, for all except one (.45 for Konzentrationstest at Occasion 2), communalities were near .6 or higher, the factor solutions can be considered to be reliable regardless of sample size (Guadagnoli & Velicer, 1988, as cited in Field, 2013). In addition, the adequacy of the sample size

Table 5. Results of the analysis of variance that was conducted to test the effect of Group in comparison with the results of children with childhood apraxia of speech (CAS) at Occasion 2 and typically developing children at Occasion 1.

Function	Dependent variable	*df*s	*F*	η^2
Complex sensorimotor & sequential memory tasks	Multivariate	4, 28	9.89***	.59
	Auditory rhythm–total	1, 31	36.01***	.54
	Hand movements	1, 31	2.91	.09
	Number recall	1, 31	12.44***	.29
	Word order	1, 31	13.29***	.30
Simple sensorimotor tasks	Multivariate	4, 29	1.88	.21
	Finger tapping	1, 32	2.84	.08
	Oral sensory	1, 32	3.53	.10
	Finger localization–1 finger	1, 32	2.29	.07
	Finger localization–2 fingers without looking	1, 32	3.87	.11
Control tasks	Multivariate	3, 30	6.57**	.40
	Labyrinths[a]	1, 32	15.26***	.32
	Spatial memory	1, 32	0.06	.002
	Attention: mean row time	1, 32	0.87	.03

[a]The scores on labyrinths are significantly higher in children with CAS (Occasion 2) as compared with typically developing children (Occasion 1).
**$p < .01$. ***$p < .001$.

was also tested by the KMO measure of sampling adequacy. For both occasions, the test yielded a value well above .8 (Occasion 1: KMO = .83; Occasion 2: KMO = .85). Furthermore, all KMO values for individual variables were .68 or higher, well above the acceptable limit of .5 (Field, 2013). Adequacy of correlations was verified by investigating the correlation matrix and by Bartlett's test of sphericity. For both occasions, Bartlett's test indicated the overall correlations between variables to be significantly different from zero, Occasion 1: $\chi^2(45) = 229.6$, $p < .000$; Occasion 2: $\chi^2(45) = 150.1$, $p < .000$. A closer inspection of the correlation matrix confirmed this result, showing all but a only a handful of correlations to be between .4 and .8. From these results, we can conclude that sample size and correlations between variables were adequate. Hence, the reliability of the factor solutions can be safely assumed. However, it should be noted that although sample size was found to be adequate for the analyses, the rather small number of cases ($n = 34$) does limit the generalizability. The results thus have to be considered with some reservation.

At Occasion 1, the two factors accounted for 72.7% of the variance. Factor 1 accounted for 40.9% of the variance (eigenvalue = 6.05), and Factor 2 accounted for 31.8% of the variance (eigenvalue = 1.21). Table 6 shows the factor loadings after orthogonal (varimax) rotation.[4] Each variable loaded on at least one factor (factor loading ≥ .50). On the basis of each variable's highest factor loadings (which are printed in bold in Table 6), Factor 1 comprises complex sensorimotor and sequential memory functions and the finger localization task. The interpretation of this result is that the finger localization task includes the localization of two fingers, which is also related to sequential memory because this is required to indicate the order of the finger touching. Factor 2 consists of the remaining simple sensorimotor tasks and control tasks.

Correlations were determined between the factor scores of the two factors and speech data obtained during the first recording session. Significant correlations were found of the first factor with monosyllabic maximum repetition rate (MRR; $r = .50$, $p = .003$, $n = 32$) and with trisyllabic MRR ($r = .69$, $p < .001$, $n = 32$), which indicates that the faster the repetition rate, the higher the scores on complex sensorimotor and sequential memory tasks. A significant (negative) correlation was also found for Factor 1 with number of consonant substitutions in meaningful utterances ($r = –.72$, $p < .001$, $n = 34$), number of substitutions in place of articulation in meaningful utterances ($r = –.59$, $p < .001$, $n = 33$), number of consonant substitutions in nonsense utterances ($r = –.77$, $p < .001$, $n = 29$), and number of substitutions in place of articulation in nonsense utterances ($r = –.67$, $p < .001$, $n = 29$). These significant correlations indicate that the higher the number of consonant substitutions, the lower the scores on complex sensorimotor and sequential memory tasks. Factor 1 did not show significant correlations with number of substitutions of manner or voicing in meaningful utterances. Factor 2 did not significantly correlate with the speech data.

[4]We also conducted oblique rotations because we did not know beforehand whether the factors were correlated. This resulted in similar distributions of factor loadings; therefore, the results were not displayed or discussed here.

Table 6. Factor scores of the variables on Occasion 1 and Occasion 2.

	Occasion 1		Occasion 2	
Variables	**Factor 1**	**Factor 2**	**Factor 1**	**Factor 2**
Auditory rhythm–total	**.88**	.32	.15	**.77**
Hand movements	**.75**	.38	.46	**.61**
Number recall	**.83**	.35	.15	**.89**
Word order	**.84**	.11	.28	**.82**
Finger tapping	.34	**.72**	**.63**	.43
Oral sensory	.40	**.65**	**.78**	.10
Finger localization: total	**.80**	.31	.54	**.59**
Labyrinths	.04	**.90**	**.80**	.13
Spatial memory	.57	**.65**	**.76**	.35
Attention: mean row time[a]	–.36	**–.73**	**–.61**	–.27

Note. Extraction method: principal component analysis. Rotation method: varimax with Kaiser normalization. The variables' highest factor loadings are shown in bold type.

[a]The polarity of this variable is reversed relative to the other variables (i.e., high performance corresponds to low scores).

The factor analysis on the data of Occasion 2 also resulted in two factors. The overall solution accounted for 64.1% of the variance. Factor 1 accounted for 32.3% (eigenvalue = 5.16), and Factor 2 accounted for 31.8% (eigenvalue = 1.25). Looking at the factor loadings in Table 6, the factors of Occasion 2 show similar patterns as compared with Occasion 1 but in the opposite direction: Factor 2 now comprises the complex sensorimotor and sequential memory tasks. Replication of the factor patterns increases the confidence in the results of the factor analyses.

Discussion

The aim of the present study was to investigate cognitive dysfunctions additional to the speech problems in children with CAS compared with typically developing children. The question was whether particular nonspeech dysfunctions are directly related to similar dysfunctions in the speech domain. Three approaches were used: (a) the comparison of cognitive functioning between children with CAS and typically developing children, (b) the development of cognitive functioning to address the issue of delay versus deviance, and (c) the coherence of the profile of the distinguished cognitive dysfunctions in relation to the severity of speech involvement.

With respect to the first question, our study showed overall poorer results in children with CAS as compared with typically developing children. Although both groups showed improvement at Occasion 2, at 15 months after Occasion 1 (mean age = 5;8), the scores of the children with CAS were still lower overall than those of the typically developing children, except for simultaneous memory, for which the CAS children had caught up with the typically

developing children. These results suggest that children with CAS show a delay that remains more or less stable during development.

In order to address the second question (i.e., whether children with CAS show an overall delay or a specific deviance), the results of the children with CAS on Occasion 2 were compared with those of the typically developing children on Occasion 1. We hypothesized that complex sensorimotor and sequential memory functions are related to CAS and would show a deviance, whereas the other simple sensorimotor functions and those unrelated to speech, such as attention and spatial memory, would only show a delay in development. The results supported our hypothesis. First, the results showed that children with CAS at Occasion 2 performed poorer with respect to the complex sensorimotor and sequential memory functions even when compared with younger typically developing children. Second, the children with CAS performed equal to younger controls on the simple sensorimotor and control tasks. These findings indicate that children with CAS show a delay but can catch up with respect to the simple sensorimotor and control tasks. However, with respect to more complex motor and sequential functions, their development is deviant, and they persistently performed more poorly.

Delay in development can be interpreted as a concomitant effect of a disorder in a rather general sense. Locke (1994) reviewed results of various studies reporting that children with language delays had poorer performance on tasks that seemingly had nothing to do with language. He suggested that compensatory activity resulting from the language deficit competes with other activities that consequently suffer from this competition, a phenomenon also called *crowding* (Locke, 1994). Such a mechanism might also explain the results of the present study (i.e., the speech deficit in children with CAS draws upon other functions to such an extent that this may cause a delay in the development of those functions). From a different perspective, minor fine motor difficulties might have played a role in the lower test scores of children with CAS, who have a higher risk of motor involvement, in the control tasks, especially the attention task in which figures had to be crossed out with a pencil. Vinck et al. (2010) showed that minor motor requirements can have large effects on test performance of children with motor difficulties, such as those due to spina bifida; after removing the motor requirements by administering the task in a computerized version, performance normalized. In the present study, this possible confounding could have added to the found delay in the control tasks.

As to the possibility of a specific relationship between some of these cognitive functions and severity of speech involvement, the third question of the present study, the cohesion between diverse cognitive functions was investigated using factor analyses. A factor analysis at Occasion 1 resulted in two factors, which could be described as follows: Factor 1 comprised complex sensorimotor and sequential memory functioning; Factor 2 consisted of simple sensorimotor and memory functioning and attention. Furthermore, Factor 1 and speech scores were significantly correlated, indicating that the speech disorder CAS is strongly associated with poor functioning on complex sensorimotor and sequential memory functions. The results of the factor analysis at Occasion 2 showed a similar pattern, showing that the correlation between functions does not seem to change during development.

In summary, the results of the different analyses all corroborate the suggestion that children with CAS as compared with typically developing children are impaired on complex sensorimotor and sequential memory functions: All children with CAS had concomitant deficits on sequential functions. These findings replicate and extend previously reported findings of impaired sequential processing in children with familial CAS (Peter et al., 2013; Peter & Raskind, 2011). Given that the current study involved Dutch-speaking participants, whereas previous studies were conducted with English-speaking samples, this constitutes an interesting convergence of findings across languages. Peter and colleagues reported slower speeds during alternating as compared with repetitive sequential motor tasks in both articulatory and finger movements, investigating several multigenerational families with a history of speech difficulties consistent with CAS (Button et al., 2013; Peter et al., 2013; Peter & Raskind, 2011). In another multigenerational family with familial CAS, they found differences in sequential processing between affected and unaffected family members on a variety of task domains, including speech motor, hand motor, imitation, reading, and spelling. Affected family members performed more poorly than unaffected family members, and the differences were found to be larger in the tasks with high sequential processing loads as compared with the low-load tasks. We find it interesting that these studies also indicate that although their conversational speech has normalized, adults with a history of CAS still show residual effects of global sequential processing deficits (Button et al., 2013; Peter et al., 2013).

The present results contribute to the discussion of whether CAS can be viewed as a separate entity or unitary disorder (ASHA, 2007; Shriberg et al., 2012) with associated problems (comorbidity) or as a symptom complex arising from a variable (across individuals) but consistent set of underlying deficits. Thus, there are two options: (a) CAS is a unitary disorder, most likely a disorder of sequencing speech movements, with a nonverbal sequential comorbidity in most children with CAS. (b) CAS is a symptom complex, primarily comprising errors of sequencing at diverse levels of speech movements (segmental, syllabic, suprasegmental); there is no single, common underlying deficit for all children with CAS, but the symptom complex can be the result of different, specific underlying deficits, followed by different possible developmental trajectories (Maassen, 2002). Diversity with respect to the association between general sequencing deficits and speech deficits has been reported in the literature. Due to this diversity, which is further discussed and elaborated in the following paragraphs, the notion of CAS as a unitary disorder seems no longer tenable.

Thus, Williams and Bishop (1992) showed that both simple and complex manual tasks were slower in children who stutter and children with other articulation disorders as compared with typically developing children. Of note, the children who stutter showed more variability than their typically developing peers, but the children with other articulation disorders did not. More recently, Newmeyer et al. (2007) found abnormal fine motor function in general in 32 preschool-aged children with severe speech sound disorder (which includes CAS). In addition, their results indicated that below-average fine motor performance was associated with below-average oral–motor imitation skills.

It is difficult to determine whether these diverse results are due to differences in tasks administered and measures used or differences in interpretation. Aram and Horwitz (1983) used construction tasks, whereas Dewey et al. (1988) and Bradford and Dodd (1996) tested transitions between sequences of movements. Williams and Bishop (1992) tested the speed and variability of simple and more complex sequences of finger and hand movements. Newmeyer et al. (2007) used the Grasping, Object Manipulation, and Visual–Motor Integration subtests from the Peabody Developmental Motor Scales–Second Edition (Folio & Rebecca, 2000). Furthermore, studies differed with respect to the selection of children on parameters such as age and speech characteristics. For example, Aram and Horwitz (1983) and Williams and Bishop (1992) studied children within a wide age range (4;4–13;2 and three groups age 5;0–10;0, respectively), whereas the age-ranges in Dewey et al.'s (1988), Bradford and Dodd's (1996), and Newmeyer et al.'s (2007) studies were much smaller: 4;5–7;1, 3;2–6;7, and 2;1–6;0, respectively. Dewey et al. (1988) showed that a second group of children with severe difficulty in speaking but without evidence of CAS (average age = 5;5) did not show a generalized motor impairment. They suggested that the speech problem of these children was probably related more to a language or phonological planning problem. In contrast, Bradford and Dodd (1996) found that children with speech-language problems other than CAS showed similar low scores on sequencing oral and verbal movements, and there is a growing body of evidence of comorbid motor impairments in children with developmental speech and language disorders other than CAS (e.g., Bishop, 2002; Hill, 2001; Müürsepp, Ereline, Gapeyeva, & Pääsuke, 2009; Visscher, Houwen, Scherder, Moolenaar, & Hartman, 2007; Webster et al., 2006; Webster, Majnemer, Platt, & Shevell, 2005). In the present study, we found a specific association between sequential memory and speech production.

Turning to the role of memory, Hulme and Roodenrys (1995) argued that children with other developmental speech-language disorders than CAS who did not exhibit motor sequencing difficulties also had memory deficits, demonstrating dissociation of memory and motor sequencing. Furthermore, Dewey et al. (1988) found in the children with CAS they studied that the generation of sequences from memory was performed equally poorly as producing spontaneous sequences, thereby questioning the role of memory in poor sequencing. A recent study by Shriberg et al. (2012) corroborates this view. In a nonword repetition task, children with CAS showed significantly lower memory (the storage and retrieval of speech representations), transcoding (planning/programming), and representational auditory–perceptual encoding scores compared with controls at the group level, but the three measures were not associated. These results were interpreted as "supporting their potential for independent contributions to descriptive-explanatory accounts of CAS" (Shriberg et al., 2012, p. 473).

Raine et al. (1991) proposed a different suggestion about the relation between memory and sequencing. They interpreted the lower short-term memory capacity in speech-disordered children to be causally related to a slow speech rate. This view was also supported by Hulme and Roodenrys (1995), who suggested that the development of verbal short-term memory skills seems to be intimately related to the development of speech production (and speech perception) mechanisms. Furthermore, both Gathercole and Baddeley (1990) and Couture and McCauley (2000) found poorer recall performance in children with phonological impairments, which they attributed to interactions between short-term memory processes and aspects of phonological (long-term) storage. Thus, short-term memory deficits have been reported in studies on speech disorders as well as language disorders, which questions the specificity of the relation between short-term memory deficits and CAS.

These results were corroborated and extended in a recent Dutch study that investigated the Sensory Profile in a broad group of 116 children with speech-language disorders compared with an age-matched control group of 116 typically developing children (Taal, Rietman, van der Meulen, Schipper, & DeJonckere, 2013). Although no objective data from direct observations of children with CAS have been available to date, these findings from parent/caretaker questionnaires imply that CAS might be associated with a passive self-regulation strategy to deal with low neurological thresholds.

Furthermore, studies indicated that production symptoms and perceptual acuity are associated in children with CAS. More specifically, Raaymakers and Crul (1988) found that the children with poorer articulation proficiency on the /-ts/ cluster showed more variability in the perception of the /-s/–/-ts/ contrast. Groenen et al. (1996) found a similar specific relation between the perception and production of place-of-articulation errors children with CAS. These results are in line with the general finding that the articulatory proficiency of speakers producing a contrast is related to their perceptual ability to discriminate the contrast (Perkell, Guenther, et al., 2004; Perkell, Matthies, et al., 2004), and similar relationships between speech perception and production measures have been found for children diagnosed with phonological disorder (Edwards, Fox, & Rogers, 2002; Nijland, 2009).

In conclusion, the results of the present study indicated a deviant development in complex sensorimotor and sequential memory functioning in the group of children with CAS that was significantly correlated with severity of

speech involvement. In addition, the children with CAS showed a delay in the development of other cognitive functions. These results suggest that CAS involves a symptom complex that not only comprises errors of sequencing speech movements but implicates comorbidity in nonverbal sequential functioning in most children with CAS.

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Appendix A

Descriptive Data of Individual Children, Including Language Comprehension (Reynell Test), Language Production (Schlichting Test), Auditory Memory, Audiometrics, Maximum Repetition Rate (MRR), and Consonant Substitution During Imitation of Meaningful and Nonsense Words

Children with CAS				Reynell language comprehension		Schlichting language production						MRR		Meaningful utterances				Nonsense utterances			
Child	Age 1	Age 2	Gender	CQ	diff age	SQ	diff age	WQ	diff age	Mem. Q	Audio	Monosyll	Tri-syll	Subcons, %	Place, %	Manner, %	Voicing, %	Subcons, %	Place, %	Manner, %	Voicing, %
1	4;11	6;4	M	102	0;02	87	–0;11	86	–0;08	96	Moderate	3.53	1.93	26.15	76.47	58.82	23.53	46.97	67.74	48.39	38.71
2	5;0	6;1	M	92	–0;05	85	–1;01	88	–0;08	89	Good	4.12	3.38	23.88	56.25	37.50	31.25	63.64	78.57	64.29	47.62
4	5;0	6;3	M	86	–0;10	82	–1;04	88	–0;08	96	Moderate	3.70	–	21.74	93.33	53.33	33.33	50.00	84.85	60.61	51.52
8	5;2	6;4	M	105	0;05	82	–1;05	80	–1;01	82	Good	0.00	0.00	8.70	66.67	66.67	33.33	33.33	50.00	50.00	35.00
9	5;2	6;5	F	80	–1;05	73	–2;02	69	–1;06	75	Good	2.70	–	14.10	45.45	54.55	36.36	—	—	—	—
10	5;4	6;8	F	99	–0;03	73	–2;02	93	–0;05	96	Good	2.48	–	10.77	14.29	28.57	100.00	18.18	41.67	25.00	83.33
11	5;4	6;10	M	94	–0;04	71	–2;05	92	–0;06	89	Moderate	4.61	–	39.13	70.37	44.44	51.85	68.18	75.56	60.00	55.56
12	5;3	6;7	M	91	–0;08	76	–1;10	87	–0;09	104	Moderate	3.02	–	20.59	78.57	42.86	50.00	43.94	75.86	41.38	34.48
13	5;7	6;8	F	84	–1;04	73	–2;02	72	–1;06	82	Good	3.64	2.21	21.88	71.43	57.14	21.43	38.46	68.00	36.00	56.00
14	5;8	6;9	M	83	–1;04	75	–1;11	85	–1;00	96	Good	4.63	3.68	14.93	60.00	30.00	10.00	15.15	30.00	80.00	30.00
20	5;10	7;2	M	92	–0;06	69	–2;04	89	–0;10	75	Good	3.31	–	29.85	60.00	25.00	50.00	48.48	71.88	56.25	37.50
21	5;11	7;1	M	89	–0;10	73	–2;02	94	–0;09	96	Good	3.20	–	13.33	30.00	50.00	50.00	—	—	—	—
22	6;1	7;3	M	96	–0;03	67	–2;09	79	–1;05	75	Good	3.31	–	29.41	65.00	55.00	35.00	66.10	64.10	53.85	30.77
25	6;3	7;7	M	93	–0;08	66	–3;04	81	–1;07	93	Good	4.31	–	44.78	76.67	36.67	43.33	78.79	73.08	51.92	38.46
26	6;2	7;6	F	84	–1;02	66	–3;05	79	–1;09	96	Good	3.76	–	35.38	78.26	43.48	30.43	46.97	64.52	38.71	64.52
28	6;10	8;3	F	82	–1;08	66	–3;08	89	–1;07	89	Good	4.23	3.61	40.32	60.00	48.00	48.00	39.39	96.15	38.46	38.46
29	6;8	7;11	M	93	1;02	74	–2;08	100	–0;09	89	Good	3.98	–	13.85	55.56	66.67	11.11	15.15	60.00	60.00	50.00
31	5;4	6;10	F									4.06	3.65	2.90	0.00	0.00	100.00	7.58	0.00	0.00	100.00
33	5;5	7;3	M									4.23	5.26	0.00	0.00	0.00	0.00	7.58	0.00	20.00	80.00
36	4;11	6;3	M									4.85	3.68	0.00	0.00	0.00	0.00	16.92	63.64	63.64	63.64
38	5;1	6;6	M									5.12	2.69	5.97	0.00	25.00	75.00	34.85	56.52	47.83	39.13
39	6;6	8;0	F									4.85	5.21	3.28	0.00	50.00	50.00	7.58	20.00	40.00	100.00
40	4;10	6;3	F									4.36	1.58	5.80	25.00	25.00	100.00	6.06	25.00	0.00	75.00
42	5;3	6;8	M									4.74	4.05	5.19	25.00	50.00	25.00	—	—	—	—
43	6;1	7;4	F									4.51	2.89	1.56	0.00	100.00	0.00	3.03	50.00	0.00	50.00
44	5;1	7;3	M									5.64	2.35	3.17	0.00	0.00	100.00	10.61	14.29	14.29	100.00
45	5;1	7;3	M									4.22	–	11.54	66.67	44.44	33.33	—	—	—	—
47	5;9	7;3	M									4.35	4.33	0.00	0.00	0.00	0.00	—	—	—	—
49	5;10	7;4	M									4.97	3.06	1.47	0.00	100.00	0.00	12.50	0.00	16.67	83.33
51	5;6	7;0	F									4.71	–	4.48	0.00	0.00	100.00	16.67	36.36	27.27	45.45
53	5;8	7;2	M									4.49	5.03	8.47	0.00	60.00	40.00	7.58	20.00	20.00	80.00
54	4;7	6;10	M									4.29	2.83	7.46	0.00	0.00	100.00	12.12	37.50	0.00	75.00
58	5;5	6;10	M									4.44	5.08	4.69	33.33	33.33	33.33	9.09	33.33	0.00	66.67
59	6;6	7;8	M									4.56	4.05	0.00	0.00	0.00	0.00	10.61	57.14	71.43	71.43

Note. CAS = childhood apraxia of speech; CQ = comprehension quotient; diff age = age difference of the scores relative to norm-age scores; SQ = sentence production quotient; WQ = word production quotient; Mem. Q = Auditory Memory Quotient (for all quotients, >80 is considered normal); Monosyll = monosyllabic repetition (/pa/, /ta/, and /ka/), Trisyll = trisyllabic repetition (/pataka/); Subcons = percentage singleton consonant substitutions in syllable initial position; Place, Manner, Voicing = percentage substitution of place, manner, voicing of subcon; M = male; F = female. Missing data are indicated with dashes. Ages are indicated in years;months.

Appendix B

Detailed Description of Subtests

1. Complex sensory motor and sequential memory tasks

Auditory rhythm: Imitation—tapping with one hand a rhythm presented auditorily only. More complex imitation—tapping with both hands a rhythm presented auditorily and visually. Scores consist of correct responses of the preference hand, the nonpreference hand, and both hands. This subtest is similar to Peter and Stoel-Gammon (2005).

Hand movements (Kaufman Assessment Battery for Children [K-ABC]; visual–motor): Imitating a sequence of hand movements (constructed from three different hand positions) presented by the examiner; sequences increase in length and complexity. Scores consists of responses in which both sequence and number of hand movements were correct.

Number recall (K-ABC; auditory–verbal): Reproducing a series of digits in the correct sequence upon auditory presentation. The correctly reproduced sequences are counted.

Word order (K-ABC; auditory–motor): Pointing out the sequence of pictures of verbally presented words for objects. The words have to be stored in short-term memory, and the corresponding pictures have to be pointed out in the right sequence on a larger illustration. The correct responses are counted.

2. Simple sensorimotor tasks

Finger tapping: Pressing a telegraph key with the index finger of one hand as many times as possible in 10 s. This is repeated five times, and the average number of taps is calculated. This subtest is derived from a Dutch neuropsychological test battery (Peadologisch Instituut Neuropsychologisch Onderzoek bij Kinderen [PINOK]; Vieijra, König, Gardien, & de Vries, 1994); however, age norms are only available from the age of 6 onward.

Oral sensory: Identifying a three-dimensional, plastic object in the mouth. The corresponding picture has to be pointed out in a row of five pictures. Correct responses are counted. This subtest is derived from Rosenbek, Wertz, and Darley (1973).

Finger localization: Identifying which finger (or fingers) was (were) touched by the examiner, with and without looking during touching. Scores consist of the correct responses of one-finger touching with visual information, the correct responses of one-finger touching without visual information, and the correct responses of two fingers touched sequentially again without visual information. This subtest is derived from the description in Benton, Hamsher, Varney, and Spreen (1983). There are no age-norm scores available; only average scores are reported.

3. Control tasks

Labyrinths (Revised Amsterdam Children's Intelligence Test [RAKIT]): Going through a labyrinth from the entrance at one side to the exit at the opposite side with a pencil as fast as possible. This is a visual–motor test, in which perceptual integration, planning, and speed are of importance. Cumulative scores are determined, in which the time it took to pass a labyrinth is transposed into a score; the longer it took, the lower the score (Bleichrodt et al., 1984).

Spatial memory (K-ABC): Pointing out the location of pictures after disappearance. Pictures are presented for 5 s, then disappear; child must point to the position of the pictures on a page with squares (nontransparent overlay on the pictures). Correct responses are counted; norm scores only available from the age of 5 onward (Kaufman & Kaufman, 1983).

Konzentrationstest für das erste Schuljahr: Crossing out pictures of pears among apples. A page consists of rows comprising identical pictures of apples (90%) and identical pictures of pears (10%); pictures of pears have to be crossed out. Scores consist of the average time needed for the execution per row and number of omissions (Möhling & Raatz, 1974).