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Sentence memory of individuals with Down's syndrome and typically developing children

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Abstract

Background Individuals with Down's syndrome (DS) have an auditory short-term memory span disproportionately shorter than the non-verbal mental age (MA). This study evaluated the Baddeley model's claim that verbal short-term memory deficits might arise from slower speaking rates (and thus less material rehearsed in a 2 s passive store) by using the sentence memory subtest of the Stanford-Binet. Previous work had shown digit span recall speaking rate to be comparable to the examiner's slow rate (one syllable per second) for both DS and language-matched participants.
Method Thirty individuals with DS were compared to two control groups [non-verbal MA-matched and mean length of utterance (MLU)-matched] on the sentence span and speaking rate for the longest verbatim recalled sentence. Sentence stimuli were presented at a normal speaking rate.
Results The DS group had shorter sentence memory span than the MA-matched group and a faster, rather than slower, speaking rate (syllables per second) than the MLU-matched controls.

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Conclusions Language production level accounted for a substantial portion of the variance in the sentence memory span in the DS group. Thus, language production skill, rather than speaking rate, predicts variability in verbal memory span.

Keywords Down's syndrome, language production deficit, phonological loop, sentence memory, speaking rate, working memory

Introduction

Down's syndrome (DS) is a genetically based disorder arising from abnormalities of chromosome 21. Trisomy 21 is the most common (about 95%) karyotype. The other two karyotypes are mosaicism and translocation (Hayes & Batshaw 1993). The reported phenotypes of DS includes intellectual disability (ID) and asymmetric development in cognitive and language domains (Chapman & Hesketh 2000).

Chapman (1995, 1997a,b) reported that children and adolescents with DS showed expressive language deficits relative to syndrome-related cognitive deficits. Language performance of the study participants revealed a language processing dissociation favouring comprehension over production that increased with chronological age. Vocabulary comprehension (measured by the Peabody Picture Vocabulary Test) was a relative strength of adolescents with DS when compared to their syntax comprehension [measured by the Test of Auditory Comprehension of Language (TACL); Carrow-Woolfolk 1985]. Both lexical and sentence level production were depressed in comparison to non-verbal cognitive measures.

Other studies of language performance in individuals with DS confirm this behavioural phenotype. Characteristic patterns of language skills in individuals with DS include deficits in speech intelligibility (Rosin *et al.* 1988; Miller 1992; Kumin 1994; Dodd & Thompson 2001), language production compared to comprehension and non-verbal cognition, and syntax compared to lexicon and pragmatics (Cardoso-Martin *et al.* 1985; Rosin *et al.* 1988; Miller 1992; Chapman 1995; Miller *et al.* 1995; Chapman 1997a,b).

Among non-verbal cognitive skills, which are comparable to syntax comprehension or better, auditory short-term memory skills are an area of relative deficit (Marcell & Amstrong 1982; Varnhagen *et al.* 1987; Marcell & Weeks 1988; Bower & Hayes 1994; Kay-Raining Bird & Chapman 1994; Wang & Bellugi 1994; Seung & Chapman 2000). Indeed, auditory short-term memory has been proposed as a mechanism contributing to expressive language delay (Chapman 1995). An alternative view, however, is that auditory short-term memory deficits are the results of the expressive language deficit. This could happen either because speaking rate, and hence rehearsal rate, is slower; or because expressive language skill is linked to memory span through the activation of long-term linguistic knowledge. This study will investigate the relation between verbal short-term memory span for sentences and expressive language, evaluating the roles of speaking rate and expressive language skill in span length.

Poor verbal short-term memory

Several studies have demonstrated a deficit in auditory short-term memory in individuals with DS (McDade & Adler 1980; Das 1985; Hulme & Mackenzie 1992; Jarrold *et al.* 1999). Bower & Hayes (1994) reported that on a Stanford-Binet test (4th edition; Thorndike *et al.* 1986), individuals with DS showed a poorer short-term memory performance (memory for sentences and memory for digits subtest) than a control group matched on chronological age, gender, IQ and socioeconomic status.

In an attempt to improve the poorer auditory short-term memory performance of individuals with DS, Broadley & MacDonald (1993) performed a short-term memory training study with 4–18-year-old children with DS. They reported that visual and verbal rehearsal and organization training improved memory performance. An important finding of the study was not only the efficacy of memory strategy training but also the modality effect on improvement with greater improvement for the visual as opposed to the auditory modality. The results of the study provide supporting evidence for poorer verbal memory performance in individuals with DS.

To evaluate whether language production demands affected auditory short-term memory performance, Marcell & Weeks (1988) included two response types (oral and manual) and stimulus modalities (auditory and visual) in a study of digit recall. Three groups of 11 participants were matched statistically on non-verbal mental age (MA) and gender, individuals with DS, typically developing children, and individuals with ID from other aetiology than DS. Manual responding did not improve auditory short-term recall in individuals with DS. They concluded that individuals with DS have great difficulty recalling verbal information presented auditorily and that this difficulty is not attributable to the demands of speech production.

Several researchers have evaluated the poor auditory short-term memory performance in individuals with DS within Baddeley's working memory model (Jarrold & Baddeley 1997; Laws 1998; Jarrold *et al.* 1999, 2000; Seung & Chapman 2000). Here we review Baddeley's (1986, 1992) working memory model briefly.

Baddeley's working memory model

Baddeley's (1986, 1992) working memory model has three major components, a central executive and two 'slave' systems holding modality-specific information. The slave systems are a phonological loop for verbal speech input and a visuospatial sketch pad for visual input.

Central executive

According to Baddeley (1986, 1992), a prime function of the limited capacity central executive is to regulate the flow of information either between the two slave systems (the phonological loop and the visuospatial sketch pad) or among the two slave systems and long-term memory.

Visuospatial sketch pad

The visuospatial sketch pad is proposed as a means of handling visual information. When a visual stimulus is given and a verbal response is required, the visual stimulus is registered on the visual sketch pad first and then sent to the phonological loop to be converted into a verbal response.

Phonological loop

The phonological loop in Baddeley's (1986, 1992) working memory model consists of two subcomponents: the phonological input store and the articulatory rehearsal process. When auditory verbal material is presented, it is automatically registered in the phonological input store that registers verbal information passively. If visual information is presented, it enters the visual sketch pad. The phonological input store is then used only when the person articulates the visual information as verbal information, which is then automatically registered in the phonological store. The articulatory rehearsal process is considered an active process that refreshes the phonological store or converts visual information into phonological information through the articulatory process (Baddeley *et al.* 1998). Baddeley (1986) considered the articulatory rehearsal process to be subvocal rehearsal in nature.

The phonological loop accounts for the role of speech information in short-term memory. Incoming spoken language information is stored automatically in the phonological loop for later processing. Once verbal information is located in the phonological loop, it can be kept available for a short period of time without using the processing capacity of the central executive. The remaining capacity in the central executive is available to retrieve relevant information from other memory systems, including long-term memory, when necessary.

Working memory deficit

Broadley *et al.* (1995) examined the role of the phonological loop in serial word recall. They studied individuals with DS aged 4–18 years using memory tasks, such as the serial recall of words from auditory and visual stimuli. They found that there was a significant effect of word length and an acoustic similarity effect in individuals with DS. The finding was interpreted as evidence for a deficit in phonological storage and in speech-based rehearsal.

Jarrold & Baddeley (1997) reported the individuals with DS had relatively lower auditory verbal short-term memory compared to visual short-term memory, which was not explained by hearing difficulty or non-verbal ability. They concluded it was a 'selective impairment of the phonological loop component' of the working memory model (Baddeley & Hitch 1974) in individuals with DS. Jarrold *et al.* (2000) also examined verbal and visual short-term memory deficits in individuals with DS and Williams syndrome, respectively. Their findings refute any causal connections between verbal short-term memory deficit and overall language deficit in individuals with DS. They accept that there is an association between verbal short-term memory and the language production deficit. Seung & Chapman (2000) also found an association between verbal short-term memory and language production deficit in individuals with DS in the digit recall study. Jarrold *et al.* (1999) ruled out hearing is a contributing factor by comparing auditory vs. visual presentation. Speech production difficulties were ruled out by comparing spoken recall with a serial recognition procedure.

Vicari *et al.* (1995) reported a reduction in central executive processing in individuals with DS compared to MA-matched controls and individuals with ID from other aetiologies. Participants' mean MA was 5.3 (DS), 5.1 (ID) and 5.5 years (MA-matched controls). Mental age was measured by Leiter Performance Intelligence Scales (Leiter 1979). Immediate recall of spatial (i.e. Corsi block tapping test) and verbal sequences (i.e. digit span) were tested using forwards and backwards recall tasks. In backwards recall, the participant was asked to recall the sequences of stimuli presented backwards. It was expected that the backwards recall task would use resources from central executive processing. The result was a deficit in backwards recall in individuals with DS in both visual and verbal recall conditions compared to the MA-matched controls and ID group.

Auditory short-term memory span: relation to language production deficit

The finding that both auditory short-term memory span and language production skills are deficits, relative to performance in other domains, has led investigators to suggest that the memory span limits play a causal role in limited language production in individuals with DS (see review by Chapman 1995). However, the way in which this relationship might arise is unclear. The Baddeley's (1992) working memory model argues for a potential relationship in which slower speaking rates could actually bring about the auditory short-term memory deficit, as a consequence of restrictions on the amount of material which could be retained in the passive phonological store (a time-limited buffer) by subvocal rehearsal. A slower speaking rate would limit the number of items that could be rehearsed before decay of passive store.

Seung & Chapman (2000) examined speaking rate in an effort to examine a mechanism of the working memory deficit using the digit span subtest of the Illinois Test of Psycholinguistic Abilities (Kirk *et al.* 1968). They tested a hypothesis of slow speaking rate as a factor for the auditory short-term memory deficit in individuals with DS (Snowling *et al.* 1991; Chapman 1995).

The current study addresses the question through measurements of speaking rate based on sentence recall for sentence stimuli spoken at a normal presentation rate, thus providing a stronger test of the hypothesis that slower speaking rates might be related to the DS group's auditory memory span deficit. Furthermore, the question of which variable(s) predict the lower verbal memory performance in individuals with DS was examined. The current study specifically looked at how the variability in sentence span is related to the variables of phonological loop (recall duration and speaking rate in syllables per second), non-verbal MA, language production level [indexed by mean length of utterance (MLU)] and language comprehension level (indexed by TACL total score). The following research questions were asked:

1 Do individuals with DS have a deficit in auditory verbal short-term memory capacity, as measured by sentence memory span?
2 If individuals with DS have a deficit in auditory verbal memory, are poor auditory verbal short-term memory scores in individuals with DS the result of a deficit in the phonological loop, as measured by speaking rate and recall duration of the longest sentence recalled verbatim?
3 If individuals with DS have a deficit in auditory verbal memory, is poor auditory short-term memory for sentences in individuals with DS associated with a language production deficit and/or language comprehension level?

Materials and methods

Background

Individuals with trisomy 21 DS from Wisconsin and vicinity had participated four times in a longitudinal study conducted by Chapman and colleagues (Chapman *et al.* 1990, 1991, 1998; Chapman 1995, 1997a,b; Seung & Chapman 2000) since 1987. Testing took place approximately every two years. Upon their arrival at the Waisman Center, Madison, WI, a certified audiologist screened hearing and middle ear function. Hearing thresholds were obtained at 500, 1000 and 2000 Hz in sound field. Individuals with a hearing loss greater than 45 dB were excluded from the study at time 1. We audio- and videotaped the entire testing session except for audiological testing. Of the 48 individuals tested at time 1, 45 were tested at time 2, 35 at time 3 and 33 at time 4.

In this study, we first examined the potential impact of hearing status on lower auditory short-term memory performance because it is known that individuals with DS experience middle ear infections more often and have more prevalent hearing problems than normally developing children (Balkany *et al.* 1979; Dahle & McCollister 1986; Rosin *et al.* 1988; Miller 1992). Individuals with DS were divided into two subgroups based on their hearing status. Group 1 ($n = 11$) represent individuals who failed at all three frequencies at 20 dB. Group 2 ($n = 24$) was composed of individuals who passed at least at one frequency at 20 dB and passed at all three frequencies at 40 dB. In order to examine whether hearing status impacted on auditory verbal short-term memory performance, group 1 and group 2 were compared on age equivalent scores for the sentence memory subtest. As expected, mean hearing threshold at the three frequencies between the two groups was statistically significant [$t(33) = 8.5$, $P < 0.01$]. However, there was no statistically significant difference between the two groups in sentence memory performance, group 1 mean (SD) = 2.71 years (0.66) and group 2 mean (SD) = 3.22 years (0.77), $t(33) = -1.9$, $P = 0.07$ (two-tailed).

Participants

The participants in this study were the 35 individuals with DS who were tested at time 3. Two control groups (non-verbal MA-matched and language production-matched group) were included: (1) non-verbal MA-matched control group (MA group), indexed by the mean scores of the pattern analysis and the bead memory subtest on the Stanford-Binet test (4th edition, Thorndike *et al.* 1986), and (2) language production-matched control group (MLU group), who were matched on MLU in morphemes in 12-min narrative samples. The participants were essentially the same as in Seung & Chapman (2000) except for some attrition of participants in the sentence memory task owing to failure to cooperate or no correct recall responses. Consequently, a total of 30 participants in each group were utilized for the temporal and statistical analysis (see Table 1).

Material and procedures

The sentence memory subtest of the Stanford-Binet (4th edition, Thorndike *et al.* 1986) was administered as part of a 3-hour research protocol (see Seung & Chapman 2000 for details of the protocol). Standard instructions described in the test manual were followed. The participant was instructed to 'say what I say'. The examiner read each item clearly at a steady pace. No repetition of items was allowed. The instructions were slightly modified for younger children, to ensure they understood the task. The length of the sentence stimuli ranged 2–16 words. Each word also varied by number of syllables. The exact sentence stimuli presented to each participant varied owing to different basal and ceiling levels. The entire testing session was audio- and videotaped. A sound grabber PZM 180 flat microphone was placed on the table close to the participant and was connected to a Panasonic WV3260 video tape recorder and audio tape recorder.

The audio track from the video recording of the sentence memory subtest of the Stanford-Binet was digitized using CSpeech (Milenkovic 1996) with a sampling rate of 22 kHz. The video recording was used because in several cases audio segments of the sentence memory subtest for several participants were not recorded on the audio tapes as a result of technical problems.

The software program CSpeech (Milenkovic 1996) was utilized for the temporal measurements. The target segment was selected on the computer screen by placing the left cursor at the onset of the periodic

Table 1 Characteristics of participants in the current study ($n = 30$ per group)

	DS		MA controls		MLU controls	
Variables	Mean	SD	Mean	SD	Mean	SD
Chronological age	17.1	4.4	4.7	1.2	3.2	0.9
Non-verbal MA*	5.8	2.0	5.5	1.9	3.5	0.8
Language production†	3.6	1.5	5.9	1.9	3.7	1.6
Vocabulary comprehension‡	6.7	2.6	5.2	1.7	3.5	1.2
Syntax comprehension§	4.9	1.2	5.3	1.7	3.4	0.7

DS, Down's syndrome; MA, metal age; MLU, mean length of utterance.
*Stanford-Binet subtests (pattern analysis and bead memory mean; Thorndike *et al.* 1986) age equivalent score.
†MLU in morphemes from a 12-min narrative sample.
‡Peabody Picture Vocabulary Test (PPVT; Dunn & Dunn 1981) age equivalent score.
§Test of Auditory Comprehension of Language (TACL total; Carrow-Woolfolk 1985) age equivalent score.
PPVT score between the DS and the MA controls $t = 2.81$, $P < 0.01$, TACL total score between the DS and the MA controls $t = -0.95$, $P > 0.05$.

waveform of the initial vowel or the energy burst of a consonant of the target sentence and the right cursor was located at the offset of the final vowel or consonant. Utilizing concurrent spectrograms and auditory playback, relatively precise and consistent determination of the onset and offset of the segment was obtained.

The longest item recalled verbatim by each individual was selected for data analysis. Items were excluded if there were lexical errors including substitution, omission, repetition or contraction of a word (either content or function word). Grammatical morpheme omission (e.g. omission of regular past tense -ed, third person singular -s or plural -s) was also considered to be an incorrect response with the exception of plural -s omission at the end of a sentence. This decision was made because these errors will change the sentence recall duration. Determining the end of a sentence was occasionally difficult when the speakers spoke softly. This was especially true when the final sound was a fricative. Therefore, an omission of -s at the end of a sentence was credited as a correct recall.

Reliability of temporal measurements

Reliability of the temporal measures was obtained by remeasuring recall duration for all participants by the same person (intrajudge reliability). The difference between measure 1 and measure 2 was defined as *D*. A distribution of absolute value of *D* for recall duration was obtained separately and the *D* value that yielded 90% intrajudge reliability was selected from the distribution as the cut-off for agreement between measures 1 and 2. When *D* values were ≤105 ms for recall duration, they were considered to be in agreement between measures 1 and 2. In any instance where a difference between the two measurements was greater than the agreement criterion, the measurements were rechecked and the third measure was adopted for statistical analysis.

Mapping between dependent variables and the phonological loop

The passive phonological store was evaluated using recall duration. If a participant recalled a sentence verbatim, she/he was assumed to have maintained the sentence in passive phonological store. The requirement to repeat the sentence immediately and the conversational rate of sentence presentation were thought to preclude rehearsal. Therefore, recall duration of the longest verbatim sentence recalled was interpreted as an index of the maximum intact verbal memory trace. Speaking rate has been identified as the index of rehearsal rate in several studies (Hulme & Tordoff 1989; Hulme *et al.* 1991). Maximum speaking rate, usually measured by asking a participant to repeat a list of words, nonsense words or syllables as fast as one can within a limited time period, was often assumed to reflect subvocal rehearsal rate (McDougall *et al.* 1994).

Baddeley *et al.* (1975) reported the 'word-length effect' that participants recalled more words when the words consisted of fewer number of syllables. Unlike the digits in the digit span task (Seung & Chapman 2000), which were all single syllables (except 'seven'), the number of syllables in the sentence stimuli varied considerably. The number of syllables in each correctly recalled sentence was therefore counted. Because speakers may vary in the actual number of syllables produced for each word, syllable counts were obtained directly from each speaker's productions by a native English speaker who was experienced in phonetic transcription.

Dependent variables

The operationally defined dependent variables for the study were:

• sentence span: number of syllables in the longest sentence recalled correctly;
• recall duration (in milliseconds): the duration between the initiation and completion of spoken recall of the longest sentence by the participant;
• speaking rate (in syllables per second): number of syllables in the longest sentence correctly recalled were divided by the recall duration in seconds.

Results

SPSS-X (10th edition; SPSS Inc. 2000) was used for the statistical analysis of the sentence memory data. Sentence memory span and speaking rate were subjected to the one-way ANOVA using the group (DS, MA and MLU group) as a between subject factor. The results were significant for memory span in syllables, $F(2, 87) = 19.37$, $P < 0.001$ and speaking rate in syllables per second, $F(2, 87) = 4.61$, $P < 0.05$.

Sentence span

Sentence memory span measures of the number of syllables in the longest sentence recalled verbatim are presented in Table 2. The differences in memory span between the DS group and the two control groups were then examined. The planned *t*-tests between the DS group and MA controls were significant, $t(58) = -5.54$, $P < 0.01$ (one-tailed), but the planned *t*-test between the DS group and MLU controls was not significant. Individuals with DS, as a group, demonstrated a shorter sentence memory span than that of the MA controls, but the sentence memory span of the DS group was not shorter than that of the MLU controls. This result supports the prediction that memory span would be shorter than expectations based on non-verbal MA for individuals with DS.

Speaking rate

Speaking rate was measured in syllables per second. Findings for speaking rate are presented in Table 3. Based on the significant result of the univariate ANOVA for speaking rate in syllables per second, the planned *t*-tests were performed on speaking rate in syllables per second. The difference between the DS group and the MLU controls was significant, $t(58) = 2.84$, one-tailed $P < 0.01$, but the difference between the DS group and the MA controls was not significant. Speaking rate in the DS group was faster than MLU controls, rather than slower, but was similar to the MA group, which does not support the slower speaking rate hypothesis as an explanation for reduced span for stimuli such as digits presented at slow rates that would permit rehearsal.

Table 2 Sentence memory span in syllables by group ($n = 30$ per group)

Group	Mean (SD)	Median	Mode (n)
Down's syndrome	5.73 (2.21)	5	5 (6)
MA controls	10.37 (4.01)	12	13 (9)
MLU controls	6.13 (3.10)	5	4 (7)

MA, mental age; MLU, mean length of utterance.

Recall duration

Recall duration was the time elapsed between the initiation and end of the recall response. Recall duration results are presented in Table 4. The recall duration of the MA group was significantly longer than that of the DS group, $t(58) = -4.61$, $P < 0.01$ (one-tailed). The recall duration between the DS and the MLU group was not significantly different.

Multiple regression analysis

Multiple regression analyses were conducted to predict sentence memory span from language production level, non-verbal MA, speaking rate and syntactic comprehension in two groups, the participants in the DS and the typically developing children, combining MA and MLU controls. The first set of predictors (model I) were MLU, non-verbal MA and speaking rate; and the second set of variables (model II) were MLU, MA, speaking rate and syntactic comprehension (TACL total score). Correlations among the variables (MLU, sentence span, speaking rate, recall duration, MA, AGE and TACL) are presented in Table 5 (DS group) and Table 6 (control group).

In the DS group, MLU accounted for 56% of the total variance (adjusted $r^2 = 0.55$, standard error of

Table 3 Speaking rate (in syllables per second) by group ($n = 30$ per group)

Group	Mean (SD)
Down's syndrome	3.38 (0.98)
MA controls	3.26 (0.82)
MLU controls	2.76 (0.69)

MA, mental age; MLU, mean length of utterance.

Table 4 Recall duration (in millisecond) by group ($n = 30$ per group)

Group	Mean (SD)
Down's syndrome	1852.8 (980.0)
MA controls	3300.5 (1414.0)
MLU controls	2225.1 (950.6)

MA, mental age; MLU, mean length of utterance.

Table 5 Correlation matrix in the Down's syndrome group

Variables	AGE	MLU	RD	Span	SR	MA
AGE	1.00	–				
MLU	0.47**	1.00				
RD	0.31	0.28	1.00	–		
Span	0.49**	0.75**	0.62**	1.00	–	
SR	0.13	0.23	-0.58**	0.15	1.00	–
MA	0.53**	0.63**	-0.07	0.38*	0.34	1.00
TACL	0.60**	0.81**	0.10	0.57**	0.31	0.81**

AGE, chronological age; MLU, mean length of utterance in morphemes from a 12-min narrative sample; RD, recall duration; span, sentence recall span in number of syllables; SR, speaking rate; MA, non-verbal mental age; TACL, Test for Auditory Comprehension of Language total age equivalent score.
$^*P < 0.05$, $^{**}P < 0.01$.

Table 6 Correlations matrix among variables in the typically developing group (combined control groups)

Variables	AGE	MLU	RD	Span	SR	MA
AGE	1.00	–				
MLU	0.60**	1.00				
RD	0.69**	0.53**	1.00	–		
Span	0.79**	0.62**	0.88**	1.00	–	
SR	0.33*	0.34**	-0.07	0.37**	1.00	–
MA	0.89**	0.57**	0.68**	0.78**	0.31*	1.00
TACL	0.86**	0.64**	0.71**	0.79**	0.30*	0.89**

AGE, chronological age; MLU, mean length of utterance in morphemes from a 12-min narrative sample; RD, recall duration; span, sentence recall span in number of syllables; SR, speaking rate; MA, non-verbal mental age; TACL, Test for Auditory Comprehension of Language total age equivalent score.
$^*P < 0.05$, $^{**}P < 0.01$.

estimate = 1.48, beta = 0.75, $t = 6.0$, $P < 0.001$) of sentence memory span in model I. Adding syntactic comprehension in model II did not change the total variance accounted for (56%) in the DS group. None of the betas (standardized coefficients) was significant for MA ($t = -0.89$), speaking rate ($t = -0.15$) or language comprehension ($t = 0.23$). However, in the typically developing group, non-verbal MA accounted for 60% of the variance (adjusted $r^2 = 0.59$, standard error of estimate = 2.66, beta = 0.77, $t = 9.2$, $P < 0.001$) in model I and language production level added additional 4% to the total variance accounted for in model II. Neither the beta for speaking rate (beta = 0.09, $t = 1.1$) nor the beta for language comprehension (beta = 0.36, $t = 2.0$) was significant. The multiple regression results suggest that the lower sentence memory span of the individuals with DS can be attributed to their poorer language production level. The typically developing children recalled sentences of lengths predicted by their non-verbal MA.

Discussion

The results for speaking rate in the present study yielded a significant difference between the DS group and the MLU group. However, the speaking rate of the DS group was faster, rather than slower, than that of the MLU group, ruling out slow speaking rate as the cause of deficit in auditory short-term memory in individuals with DS. As indicated in the multiple regression results, non-verbal MA predicts the sentence memory span in the typically developing children. However, in the individuals with DS whose sentence memory span is lower than the MA group, their language production levels, not their speaking rate, predict the sentence memory span.

Long-term memories for language (Thorn & Gathercole 1999), lexical content (Gathercole *et al.* 2001) and phonotactics (Gathercole *et al.* 1999) play a role in auditory short-term memory, and differences in phonological memory skill are correlated with language skill and affect new learning (Adams & Gathercole 2000; Willis & Gathercole 2001).

Deficits in passive phonological store, intentional rehearsal or automatic rehearsal loop?

Individuals with DS had a shorter sentence memory span than the MA group would predict. Given their speaking rate similar to the MA group, their shorter recall duration is an expected consequence. If we assume that no automatic or intentional rehearsal process took place in this task, and that size of phonological store is independent of level of long-term knowledge of language production, then these results suggest that the locus of working memory deficit in individuals with DS lies in a shorter passive phonological store that holds information for short period of time while the information is stored in the short-term memory, rather than in the articulatory rehearsal loop. Alternatively, long-term language production knowledge may contribute to the size of phonological store, or to the functioning of an automatic rehearsal loop including early motor areas; or intentional rehearsal may have taken place. We explored these possibilities.

Working memory deficits in individuals with Down's syndrome: secondary to a language production deficit?

In an effort to examine the contribution of impaired language production of individuals with DS to the reduced sentence memory span, two models were tested. Model I included language production level, non-verbal MA and speaking rate. Predictors in model II included syntactic comprehension level in addition to the predictors in model I. Results of the multiple regression analyses demonstrated that language production level was the strongest predictor in the DS group. In the control group, non-verbal MA predicted sentence memory span in model I, and non-verbal MA and language production level predicted sentence memory in model II. These results are interpreted to mean that the working memory deficit in individuals with DS was associated with their language production deficit, rather than speaking rate.

Comparison of the digit span and sentence memory span findings

In the current study, the speaking rate of the DS group was not slower than that of the MA group but rather was faster than that of the MLU group. The results of the current study suggest that individuals with DS (mean chronological age of 16 years) did not have a deficit in speaking rate (in syllables per second) compared to their MA-matched control group (mean chronological age of 4 years) whose sentence memory span is longer than that of the DS group. But they rather showed a faster speaking rate compared to MLU controls (mean chronological age of 3 years) whose sentence memory span was not different from that of the DS group. This result may be related to a difference in age-related neuromuscular developmental level (Tsao & Weismer 1997) between the individuals with DS and the MLU group.

The second finding of the present study was that sentence span was longer than digit span in all three groups, but the difference between digit span and sentence span was greater in the MA group than in the other groups (mean digit span was four, five and three digits for the DS group, MA and MLU controls, respectively (see Seung & Chapman 2000); the corresponding mean sentence spans were six, 10 and six syllables for the DS group, MA and MLU controls, respectively). This result may reflect the contribution of semantic and syntactic knowledge that was not available in a string of digits.

In summary, the results of the two studies suggest deficits in both passive phonological store (as measured by recall duration) and deficits in memory span of individuals with DS, but language production skills, rather than speaking rate, appear to be a more likely candidate cause.

Limitations

Because the sentence memory subtest of the Stanford-Binet was used to examine verbal short-term memory, each participants' temporal measurements were obtained from different stimuli owing to basal and ceiling rules of the standardized test administration. Also only the correct verbatim recalls were included in the data analysis because we were interested in examining verbal short-term memory performance at individuals' maximum capacity. However, this could have introduced some bias into the results.

Future directions

The speaking rate (syllables per second) of the DS group was not different from that of the MA controls, but was faster than that of the MLU controls. The hypothesis of no difference in speaking rate between the DS group and MA group can be further tested at a maximal rates in a follow-up study by comparing the groups on a simple speech task such as Diadochokinetic rate in which participants are asked to repeat single (e.g. /pa/, /ta/, /ka/), double (e.g. /pata/) or multiple syllables (e.g. /pataka/).

Is the contribution of the language production deficit to poor auditory short-term memory performance a unique characteristic of the DS group or is it observed in any other group of children who have language delay? Weismer *et al.* (1999) and others

(Dollaghan 1987; Bishop 1992; Dollaghan *et al.* 1993) reported that children with specific language impairment (SLI) demonstrated poorer verbal working memory (Montgomery 2000). The studies of children with SLI suggest connections between working memory and language production deficit as well.

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