Digit Span in Individuals With Down Syndrome and in Typically Developing Children: Temporal Aspects

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This study explored factors influencing digit span performance in individuals with Down syndrome. The following questions were asked: Is there a deficit in the phonological loop, either in articulatory rehearsal (measured in speaking rate and recall latency) or in the passive store (measured in recall duration)? Is reduced auditory short-term memory associated with a language production deficit? Thirty five adolescents with trisomy 21 Down syndrome were compared to 35 mental-age-matched and 35 language-production-matched controls. There was no group difference in speaking rate. The DS group had shorter digit spans than the MA controls. Language production level accounted for substantial variance in digit span in individuals with Down syndrome.

KEY WORDS: Down syndrome, digit span, working memory, phonological loop, language production deficit

Individuals with Down syndrome (trisomy 21) have several phenotypic characteristics, including mental retardation, a language production deficit, and poor auditory short-term memory. Several studies have addressed the issue of the specific language production deficit (Chapman, 1995, 1997a, 1997b). However, the nature of the mechanism underlying poor auditory short-term memory in individuals with Down syndrome has not been clear. For example, it is not known if there is a causal connection between reduced auditory short-term memory and language production deficit.

Children and adolescents with Down syndrome evidence greater expressive language deficits than syndrome-related cognitive deficits (Chapman, 1995, 1997a, 1997b). Both lexical and sentence production have been found to be more depressed than nonverbal cognitive measures. Individuals with Down syndrome produced fewer total words, fewer different words, and shorter mean length of utterance (MLU) in 12-min narrative samples than controls matched for nonverbal mental age (Chapman, Seung, Schwartz, & Kay-Raining Bird, 1998).

Individuals with Down syndrome also manifest reduced auditory short-term memory, as measured by the maximum number of digits recalled correctly. Wang and Bellugi (1994) compared individuals with

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Down and Williams syndromes whose age, IQ, and sex were matched. They reported that individuals with Down syndrome performed better in a Corsi blocks visual-spatial test (Milner, 1971) than on a verbal short-term memory test (the digit span subtest of the Wechsler Intelligence Scale for Children–Revised; Weschsler, 1974, cited in Wang & Bellugi, 1994). Marcell and Weeks (1988) reported that individuals with Down syndrome had shorter auditory verbal recall performance than controls matched for vocabulary comprehension. There was no significant difference in recall performance for the Down syndrome group whether the response modality was verbal or manual, suggesting that auditory memory rather than verbal report was the locus of the problem.

Explanations of the auditory short-term memory deficit found in individuals with Down syndrome include a deficit in remembering sequential information (Das, 1985; Rosin, Swift, Bless, & Vetter, 1988; Snart, O'Grady, & Das, 1982; Varnhagen, Das, & Varnhagen, 1987), a deficit in the storage and retrieval of auditory information (McDade & Adler, 1980), a modality effect (Marcell & Amstrong, 1982; Rohr & Burr, 1978), and a deficit in phonological working memory (Broadley, MacDonald, & Buckley, 1995). The sequential processing deficit hypothesis was tested in previous research demonstrating that individuals with Down syndrome were no more impaired in their memory for the order of visual, auditory, and story information than controls matched for mental age and level of recall (Kay-Raining Bird & Chapman, 1994).

The aim of the current study was to evaluate deficits in the phonological loop as explanations for poor auditory short-term memory in individuals with Down syndrome. Poor auditory short-term memory in individuals with Down syndrome was evaluated within the working memory model proposed by Baddeley and associates (Baddeley, 1981, 1992; Baddeley & Hitch, 1974). Baddeley's working memory model is time based. The working memory model has three major components: a central executive and two "slave" systems holding modality-specific information. The slave systems are the visuo-spatial sketch pad for visual input and the phonological loop for verbal speech input. Baddeley divided the phonological loop component into two subcomponents: the phonological input store and the articulatory rehearsal process. Baddeley (1994) assumed that the phonological loop holds speech-based information for a brief period (about 1.5 to 2 s). The articulatory rehearsal process refreshes information in the passive store, if activated. Studies of typically developing children have shown that increases in auditory memory span are correlated with increases in speaking rate (Hitch, Halliday, & Littler, 1989; Hulme & Tordorff, 1989), implicating subvocal speaking rate during rehearsal as a factor contributing to maximum span.

It was reasoned that individuals with Down syndrome might have a temporally limited passive phonological store, or fail to employ articulatory rehearsal, or rehearse more slowly than a mental-age-matched group. If articulatory rehearsal does not occur in the verbal short-term memory task, then recall performance is expected to rely solely on the passive phonological store that holds information for about 2 s. If poor verbal short-term memory in individuals with Down syndrome is related to poor articulatory rehearsal, then individuals with Down syndrome would be expected to have a slower speaking rate during verbal recall than MA-matched controls, but a speaking rate equivalent to that of MLU-matched controls.

Most researchers who have focused on speaking rate or articulation rate have collected data by using lists of words or nonwords as stimuli in forced speaking situations and asking the participants to speak as fast as possible (Dollaghan, Biber, & Campbell, 1995). In both memory and reaction time research, securing the fastest responses has been a common practice. It is assumed that this will prevent the occurrence of intervening mental processes, except for the processes of interest. By requiring a participant to respond as rapidly as possible, maximum performance can be obtained. Such requirements do not reflect natural speaking rates and, by extension, typical rehearsal rates.

To test this possibility we assumed that an overt speaking rate is an approximation of a covert subvocal articulation rate in the auditory verbal short-term memory task. And a participant's recall duration for the longest string successfully recalled was assumed to be associated with the duration of passive phonological store. Finally, we reasoned that recall latency would be related to the articulatory rehearsal process, assuming that if rehearsal occurs, it will occur during recall latency. Thus, long recall latencies should be associated with longer maximum spans.

The following specific questions are asked in the study:

1. Are poor auditory verbal short-term memory scores in individuals with Down syndrome due to a deficit in phonological working memory (phonological working memory deficit)? If so, is poor auditory verbal short-term memory performance in individuals with Down syndrome associated with a shorter phonological store (passive phonological store deficit) or poor articulatory rehearsal (slower articulatory rehearsal rate)?

2. Is poor auditory verbal short-term memory in individuals with Down syndrome associated with a language production deficit?

Method

Background

The current study was based on a longitudinal Down syndrome language development data corpus at Time 3 (the third visit) reported in Chapman (1995, 1997a, 1997b). Individuals with Down syndrome were tested every 2 years for a total of 4 visits to obtain data on various aspects of language comprehension and production. Participants were recruited in the state of Wisconsin and surrounding states. Only individuals with chromosome 21 trisomy were included in the original longitudinal study (2 with translocation and 1 with mosaicism were excluded). The information was obtained from parents' report on cytological testing. Spoken English was their primary means of communication.

When a participant arrived for Time 3 testing, he or she received the 3-hour protocol set forth in Table 1. Each participant was tested individually. The entire testing session, except for hearing screening, was video- and audiotaped. A sound grabber PZM 180 microphone was placed on the table close to the participant and connected to a Panasonic WV 3260 videotape recorder; a second one was connected to an audiotape recorder.

Table 1. Time 3 protocol.

Order	Task
1	Hearing screening
2	Comprehension strategy task
3	Peabody Picture Vocabulary Test–R[a] or Test for Auditory Comprehension of Language–R[b]
4	6-min conversation with an examiner
5	12-min narrative sample including Cookie Theft picture description, familiar story telling, and Stein stem (story completion task)
6	Priming task (first half)
7	Digit span subtest of the Illinois Test of Psycholinguistic Abilities[c]
8	Dollaghan Fastmapping task: exposure, comprehension, production, and location task
9	Milosky task (movie story retell)
10	Stanford-Binet[d] subtests of picture vocabulary, bead memory, pattern analysis, and sentence memory
11	Break/6-min conversation with parent
12	PPVT-R or TACL-R
13	Priming task (second half)
14	Fast mapping task: delayed recall
15	Story retelling task

[a] Dunn & Dunn (1981)
[b] Carrow-Woolfolk (1985)
[c] Kirk & Kirk (1968)
[d] Thorndike, Hagen, & Sattler (1986)

Hearing and middle ear function were screened by an audiologist. Hearing thresholds were obtained using warble tones at 500, 1000, and 2000 Hz in a sound field. Individuals with Down syndrome with a hearing loss greater than 45 dB at Time 1 were excluded.

The original study at Time 3 used three control groups statistically matched to the individuals with Down syndrome: nonverbal mental age matched (MA controls), language comprehension matched (TACL controls), and language production matched (MLU controls). The MA and MLU control groups were selected for the present study. There were 35 participants in each group. The language-comprehension-matched control group was not included because it was similar in mental age to the MA controls. The purpose of the current study was to examine the contribution of nonverbal cognition and language production to verbal short-term memory. Language comprehension was not of interest in the current study.

Participants

Thirty-five individuals with trisomy 21 Down syndrome between the ages of 9.8 and 24.3 years and 70 (35 in each control group) normally developing children between the ages of 2.3 and 6.8 years participated. The characteristics of the participants in the study are summarized in Table 2. For a few younger children in the MLU controls, the instruction was modified to ensure that they understood the task. For example, a participant was told that he or she was going to play a "copy cat," and the examiner presented a string of digits.

Individuals with Down syndrome experience middle ear infections more frequently than normally developing children, and they also have more hearing problems (Balkany, Downs, Jafek, & Krajicek, 1979; Brooks, Wooley, & Kanjilal, 1972; Dahle & McCollister, 1986; Fulton & Lloyd, 1968; Keiser, Montague, Wold, Maune, & Pattison, 1981; Miller, 1992; Rosin et al., 1988). Therefore, hearing status was evaluated as a confounding factor in poor auditory verbal short-term memory performance. Individuals with Down syndrome were divided into two subgroups on the basis of their hearing status. Group 1 (n = 11) consisted of individuals who failed at all three frequencies (500 Hz, 1 kHz, and 2 kHz) at 20 dB. Group 2 (n = 24) consisted of individuals who passed at least at one frequency at 20 dB and passed at three frequencies at 40 dB. In order to examine whether hearing status affected auditory verbal short-term memory performance, Group 1 and Group 2 were compared on age-equivalent test scores for the digit span subtest of the Illinois Test of Psycholinguistic

Table 2. Characteristics of participants in the current study.

Variables	Down syndrome $N = 35$ *M*	*SD*	MA controls $N = 35$ *M*	*SD*	MLU controls $N = 35$ *M*	*SD*
Chronological age	16.39	4.48	4.48	1.23	3.15	0.83
Nonverbal mental age[a]	5.58	2.02	5.26	1.86	3.36	0.81
Vocabulary comprehension[b]	4.83	2.6	4.95	1.71	3.39	1.19
Syntax comprehension[c]	4.72	1.28	5.04	1.72	3.32	0.67
Language production[d]	3.34	1.59	5.7	1.81	3.49	1.55
Sentence memory (yrs)[e]	3.06	0.76	5.64	2.72	3.71	1.85
Digit span (yrs)[f]	3.68	1.21	5.15	1.8	3.61	1.46

Note. Age equivalent scores are reported for direct comparison across tests.

[a] Stanford-Binet subtests (pattern analysis and bead memory mean; Thorndike, Hagen, & Sattler, 1986)

[b] Peabody Picture Vocabulary Test (Dunn & Dunn, 1981)

[c] Test of Auditory Comprehension of Language (TACL-total; Carrow-Woolfolk, 1985)

[d] Mean Length of Utterance in morphemes from a 12-min narrative sample

[e] Stanford-Binet subtest (Thorndike, Hagen, & Sattler, 1986)

[f] Illinois Test of Psycholinguistic Abilities subtest (Kirk & Kirk, 1968)

Abilities (ITPA; Kirk, McCarthy, & Kirk, 1968).

As expected, mean warble tone threshold at the three frequencies between the two groups was statistically significant [$t(33) = 8.5$, $p < .01$]. However, there was no statistically significant difference between the two groups in digit span performance [$t(33) = -1.9$, $p > .05$]. The mean of digit span age-equivalent scores was 3.13 ($SD = 1.04$) for Group 1 and 3.94 ($SD = 1.22$) for Group 2.

Three individuals whose warble tone thresholds were at or above 41 dB HL (moderate hearing loss according to American National Standards Institute) and who also failed at three frequencies at 20 dB were examined further for their memory performance. Those three individuals recalled lengths of 2, 4, and 4 digits respectively. Their memory span performance fell within the range of the other participants. Therefore, they were retained in the study.

Materials/Procedures

The nonverbal subtests of the Stanford-Binet were used to assess nonverbal mental age because their range extended down to 2.2 years, unlike more widely used measures. The digit span subtest of the ITPA was used instead of the digit memory subtest in the Stanford-Binet because the developmental range of the ITPA was a better fit for the age range of the longitudinal study. The age range for the digit memory subtest in the Stanford-Binet is 5.4 to 17.5 years; the digit span in the ITPA ranges between 2.2 and 10.3 years. The lower end of the range was more critical than the upper end of the norms for the Down syndrome longitudinal study.

In the digit span task, the examiner demonstrated the task to the participant by saying "Listen. Say 2-2." Each item was presented at a uniform rate of 2 digits per second. If the participant failed to respond, the examiner repeated a sequence after saying "Not quite. Try again." The basal and the ceiling of the digit span subtest in the ITPA were three consecutive successes and two consecutive failures respectively. Each participant was tested individually while a parent watched him or her through the one-way mirror in an adjacent room. When necessary, the parent stayed with the participant in the testing room.

Digitization

CSpeech (Milenkovic, 1996), a waveform analysis program, was used to digitize the analog signal of the digit span task from videotape recordings. The entire memory task was digitized at a sampling rate of 22 kHz, which means that the analog signal was converted into a digital signal 22,000 times per second (see Kent & Read, 1992, chap. 3 and 4, for additional details). Each complete recall was stored in a separate file for later acoustic analysis.

Dependent Variables

The three dependent variables were operationally defined as follows: *Recall latency* was defined as the time between the end of the examiner's utterance and the beginning of a participant's correct recall response. *Recall duration* was defined as the duration between the initiation and the end of a recall sequence for a participant.

It includes pauses within the recall response. *Speaking rate* (in digits/s) was defined as the recall duration divided by the number of digits within a correct recall response.

Mapping Between Dependent Variables and the Phonological Loop

Recall duration was selected to examine passive phonological store duration in the phonological loop. If a participant recalled a sequence of digits correctly, he or she was assumed to have an intact verbal memory trace. Therefore, recall duration would reflect passive store duration.

Recall latency and speaking rate were selected to examine the articulatory rehearsal process. If rehearsal occurred, it would occur during recall latency. Also, speaking rate was used as an estimate of subvocal rehearsal rate.

Acoustic (Temporal) Measurement

Acoustic measurements were performed using CSpeech. Measurements were made using both waveforms (15 bits of resolution) and spectrograms (generated using 300–500 Hz analyzing band widths). Measurements consisted of recall latency and the participant's recall duration in milliseconds. Cursors were used to isolate the target sentence. The left cursor was located at the onset of the periodic waveform of the initial vowel or the energy burst of a consonant of the target sentence. The right cursor was located at the offset of the final vowel or consonant. For a relatively precise and consistent determination of the onset and offset of the segment, concurrent spectrograms and auditory playback were utilized. Temporal measures were made of all complete recall responses.

Reliability of Temporal Measurements

Duration and latency for all items were remeasured for five randomly selected participants per group. Of 303 remeasurements, 281 (93%) were within ±50 ms of the original values.

Correct Response Selection

When the data were collected, each individual's recall responses were obtained with no pressure for recalling as fast as one can. Selection of the longest correctly recalled digit string is considered a method of measuring optimal/maximal performance capacity of each individual.

The longest digit string recalled correctly by each individual was selected using the following exclusionary criteria when temporal measurements were completed. Recall responses were excluded if (a) there was any filled pause by a participant before the initiation of a recall response (i.e., "um, I forgot," etc.), (b) there was a partial repetition of a target (e.g., "five two [pause] five two eight" when the target was "five two eight"), (c) the examiner had to repeat the stimulus because no response was initiated by a participant, (d) there was a speaking overlap in which a participant began digit recall before the examiner finished presenting the stimulus item. After these responses were excluded, the next highest digit span recalled correctly was selected for statistical analysis.

Participant Selection

Eight participants' performances (1 from the DS group, 3 from the MA group, and 4 from the MLU group) were excluded from statistical analysis for the following reasons. The one participant with Down syndrome used manual signs with oral speaking. He spoke only a few utterances, and most of these were unintelligible. His intelligibility in a 12-min narrative sample was 58% when intelligibility was defined as a percentage of complete and intelligible utterances divided by the number of total utterances. One participant's recording was poor because of a technical problem with a microphone, and two additional participants in the MA group were not cooperative. Two participants were not cooperative, and two in the MLU group had no correct recall.

Results

All dependent measures (recall latency, speaking rate, and recall duration) were obtained for the highest digit span recalled correctly. When there was more than one correct recall within the highest number of digits, both were measured and a mean was obtained. Because different participants received different test items and had different ceiling and basal levels, the items correctly recalled by each participant are not necessarily identical.

SPSS-X was used for statistical analysis (3rd edition; SPSS, Inc., 1988). When the three dependent measures were subjected to Multivariate Analysis of Variance (MANOVA), the omnibus test result was significant among groups [$F(6, 184) = 5.78$, $p < .001$] (Pillais-Bartlett test). Univariate test results indicated that recall latency [$F(2, 93) = 4.26$, $p < .02$] and recall duration [$F(2, 93) = 5.10$, $p < .01$] were significantly different among groups. Planned comparisons for recall latency and recall duration were carried out at a family-wise error rate of .05

alpha level (alpha of .025 for each comparison: DS vs. MA and DS vs. MLU group).

Recall Latency

Recall latency was defined as the silent interval between the end of the stimulus presentation and the initiation of the recall response. A summary of recall latency by group is presented in Table 3. A planned *t* test for a mean difference of 541 ms between the DS and the MLU groups was significant [$t(36.4) = –2.61$, two-tail p = .013; M = 1269 for the DS and M = 793 for the MLU group]. However, a mean difference of 403 ms between the DS group and the MA group (M = 866) was not significant at an alpha of .025 [$t(38.4^*) = –2.23$, one-tail p = .0265; *df for unequal variance].

Larger variability was noted in the Down syndrome group (SD = 1126 ms) than in the two control groups (SD = 328 ms in the MA group; SD = 253 ms in the MLU group). Seven individuals with Down syndrome had recall latencies longer than 2000 ms. All recall latencies in the MA and MLU controls were less than 2000 ms. When individuals whose recall latency was longer than 2000 ms were examined further, it was noted that their digit span ranged from 3 to 5 digits (see Figure 1).

Recall Duration

Recall duration was defined as the duration between the initiation and end of recall response. A summary of the recall duration of the correct recall by group is presented in Table 4. When recall duration was subjected to planned *t* tests, a difference between the DS and MA group was statistically significant [$t(64) = –2.65$, one-tail p = .005]. However, a difference between the DS and MLU group was not significant [$t(62) = –.14$, p = .888]. The longer mean recall duration in the MA controls may have been influenced by their longer mean digit span.

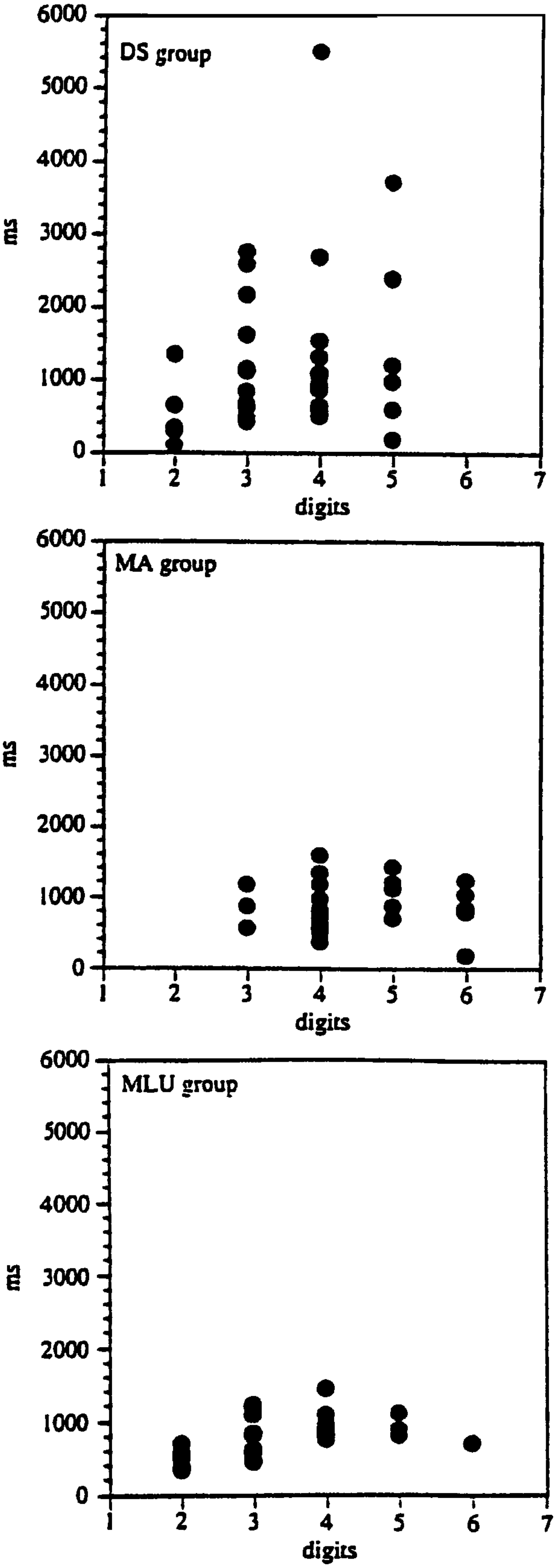
Table 3. Recall latency (in ms) by group.

Group	*M*	*SD*	*n*
DS	1269.29	1126.19	34
MA	866.03	328.31	32
MLU	793.02	252.66	30

Table 4. Recall duration (in ms) by group.

Group	*M* (*SD*)		Range	*n*
DS	2061.2	(897.6)	476.1–3704.0	34
MA	2683.1	(1011.2)	1310.8–5228.4	32
MLU	2089.9	(688.9)	759.7–3296.7	30

Figure 1. Individual recall latency at various digit spans.



Therefore, digit span for each group was examined. Digit span was defined as the maximum number of digits recalled correctly. The range of maximum digit span was from 2 to 6 digits for all participants (see Figure 1).

A summary of the digit span by group is presented in Table 5. When subjected to planned *t* tests, a difference in the digit span between the DS and MA group was statistically significant [$t(64) = -4.07$, $p = .000$]. However, a difference in the digit span between the DS and MLU group was not significant [$t(62) = .37$, $p = .709$]. The digit span of the DS group was shorter than the digit span of the MA group but similar to the digit span of the MLU group.

The influence of digit span on the effect of recall duration was examined further by using digit span as a covariate. When digit span was used as a covariate [$F(1, 92) = 90.59$, $p < .001$] digit span partialled out the group effect of recall duration [$F(2, 92) = .17$]. However, when recall duration was used as covariate [$F(1, 92) = 90.59$, $p < .001$], group effect for digit span was significant [$F(2, 92) = 5.69$, $p < .01$]. These results coupled with differences in digit span between groups support the conclusion that the significant difference in recall duration is attributable to differences in digit span (see Figure 2).

Speaking Rate

Speaking rate in digits/second was computed by dividing digits recalled correctly by recall duration. The recall duration was measured in milliseconds and converted into seconds to obtain a speaking rate measure in digits/second. Results for speaking rate in digits per second are summarized in Table 6. Speaking rate did not vary significantly among the groups [$F(2, 93) = 1.29$, $p > .05$].

Correlation Analysis

Pearson correlation coefficients among variables are summarized by group in Table 7. Recall latency in milliseconds (RL) was not significantly correlated with digit span (Span), speaking rate in digits/second (SR), recall duration in milliseconds (RD), mean length of utterance (MLU), or nonverbal mental age (MA). Recall duration was significantly correlated with digit span in all three groups; the longer the digit span, the longer the recall duration. These results validated the use of digit span as a covariate in previous sections to reevaluate significant group effects in recall duration. The recall durations were also negatively correlated with speaking rate in all three groups; the faster the speaking rate, the shorter the recall duration. Speaking rate was not significantly correlated with digit span or recall latency.

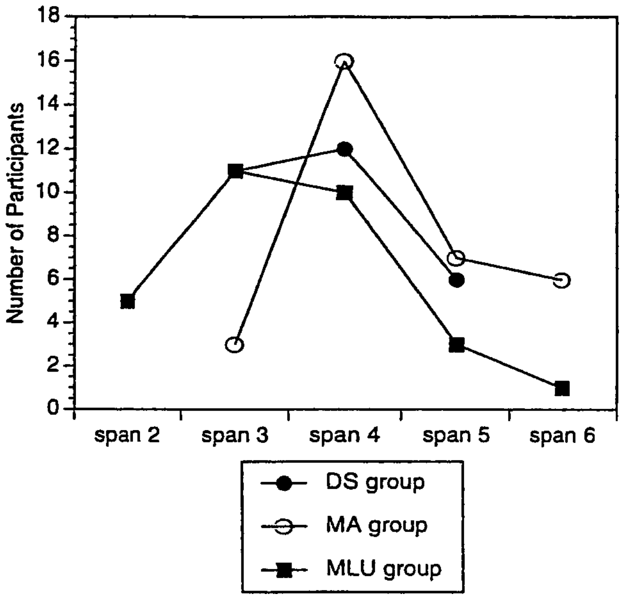
Table 5. Digit span (in number of digits) by group.

Group	*M* (*SD*)	*N*
DS	3.56 (.96)	34
MA	4.50 (.92)	32
MLU	3.47 (1.01)	30

Table 6. Participants' speaking rate (in digits/s) by group.

Group	*M* (*SD*)	*N*
DS	1.98 (.74)	34
MA	1.83 (.61)	32
MLU	1.74 (.42)	30

Figure 2. Distribution of digit spans in three groups.



Multiple Regression Analysis

Multiple regression analyses were performed to examine contributions of the measures of language production level (MLU), phonological loop (speaking rate and recall latency), and mental age in the variance accounted for in digit span performance. A forced method of regression analysis was used. Two models, Model I and Model II, were tested. The difference between Model I and Model II is the order of variables entered in the multiple regression analyses. The order of variables entered was MLU, MA, speaking rate, and recall latency in Model I and speaking rate, recall latency, MLU, and MA in Model II. Model I evaluates a contribution of language production level to digit span performance, and the Model II evaluates a contribution of the phonological loop. Results are summarized in Table 8 (Model I) and Table 9 (Model II).

Table 7. Intercorrelation matrix for each group.

Variable	MA	MLU	Span	SR	RL
		DS group (*n* = 34)			
MA	—				
MLU	.66**	—			
Span	.58**	.57**	—		
SR	–.13	–.23	–.43	—	
RL	.16	.14	.24	–.24	—
RD	.3	.44	.78**	–.82**	.23
		MA-matched control group (*n* = 32)			
MA	—				
MLU	.3	—			
Span	.53	.19	—		
SR	–.12	.19	–.02	—	
RL	–0.26	–0.19	0.1	–0.14	—
RD	0.4	–0.05	.67**	–.70**	0.16
		MLU-matched control group (*n* = 30)			
MA	—				
MLU	.68**	—			
Span	.71**	.54	—		
SR	0.24	0	0.1	—	
RL	0.08	0.21	0.41	–0.29	—
RD	0.37	0.42	.70**	–.61**	.52

**p < .001

As noted in Tables 8 and 9, 50% of the variance in digit span was explained by the four variables in the DS group, 37% of the variance in the MA controls, and 63% in the MLU controls. Language production level masked the role of the phonological loop in predicting digit span performance in the DS and MLU controls when it was entered before the phonological loop variables in the regression analysis. In Model I, once language production level accounted for the variance in digit span, the phonological loop accounted for only about a third of the variance explained by the language production level in the DS group, and a half of the variance was accounted for by the language production level in the MLU group. However, in Model II the variances accounted for by the phonological loop and the language production level were similar.

Discussion

The results of this study partially support the hypothesis of a phonological loop deficit in individuals with Down syndrome. The DS group showed a deficit in passive phonological store, as measured by shorter recall duration than the MA controls, but not in the speed of the articulatory rehearsal process as indexed by speaking rate. Recall duration of the DS group was shorter than that of the MA controls but equivalent to that of the MLU controls. The DS group failed to reveal a difference in the recall latency—unlike the MA controls. However, the recall latency of the DS group was significantly different from that of the MLU group. The DS

Table 8. Multiple regression analysis for digit span using language production level (MLU), mental age, and phonological loop (speaking rate and recall latency): Model I.

Step/ variable	R2	R2 change	F (Eqn)	sigF	Beta In
		DS group			
MLU	0.32	0.32**	15.07	0.000	0.57
MA	0.39	0.07	10.12	0.000	0.36
speaking rate	0.49	0.10	9.76	0.000	–0.32
recall latency	0.5	0.01	7.23	0.000	0.08
		MA-matched control group			
MLU	0.04	0.04	1.13	0.297	0.19
MA	0.3	0.26*	6.06	0.007	0.54
speaking rate	0.3	0.00	3.96	0.018	0.06
recall latency	0.37	0.07	3.85	0.014	0.27
		MLU-matched control group			
MLU	0.29	0.29*	11.57	0.002	0.54
MA	0.51	0.21*	13.78	0.000	0.63
speaking rate	0.51	0.00	8.94	0.000	–0.05
recall latency	0.63	0.12*	10.56	0.000	0.37

*p < .01, **p < .001

Table 9. Multiple regression analysis for digit span using variables of phonological loop (speaking rate and recall latency), language production level (MLU), and mental age: Model II.

Step/ variable	R2	R2 change	F (Eqn)	sigF	Beta In
		DS group			
speaking rate	.18	.18	7.19	.012	–.43
recall latency	.20	.02	3.98	.029	.15
MLU	.42	.22*	7.34	.001	.48
MA	.50	.08	7.23	.000	.37
		MA-matched control group			
Speaking rate	.00	.00	.001	.972	–.01
Recall latency	.01	.01	.122	.885	.09
MLU	.06	.05	.530	.666	.22
MA	.37	.31*	3.85	.014	.62
		MLU-matched control group			
Speaking rate	.01	.01	.29	.597	.10
Recall latency	.22	.21	3.90	.032	.48
MLU	.42	.20*	6.40	.002	.46
MA	.63	.41*	10.56	.000	.64

*p < .01

group took longer, on average, to initiate recall response than the MLU controls. These results were interpreted as indicating that individuals with Down syndrome do have a passive phonological store deficit in that their recall duration was shorter than the MA-matched controls. However, this interpretation requires further examination because one might argue that individuals with Down syndrome had shorter recall duration because they recalled fewer digits. The longer recall duration in the MA controls than in the DS group is associated with and attributable to the longer digit span. To resolve this issue, when digit span (the number of digits recalled) was used as a covariate, group differences in recall duration were partialled out. Furthermore, a correlation analysis showed significant association between recall duration and digit span within all three groups.

Several studies of typically developing children reported that both memory span and speaking rate increase with age. Some authors (Hitch et al., 1989; Hulme & Tordoff, 1989) have interpreted this result causally. Developmental memory span increase was attributed to speaking rate increase. More information can be stored in the phonological loop (Baddeley, 1986, 1992) by rehearsing the information faster before it decays from the passive phonological store. Therefore, a faster speaking rate prevents more information from decaying.

The result of the digit span in the current study is consistent with the findings of the developmental studies (Chi, 1976, 1977; Case, Kurland, & Goldberg, 1982; Henry & Millar, 1991) in that digit span was higher in the MA controls than the MLU controls. (Mean age of the MA controls is 4 years and of the MLU controls is 3 years.) However, the result of the speaking rate analysis in the current study was not consistent with that of the other studies. The speaking rate did not contribute to differences in the digit span performance either in an analysis of variance or in multiple regression analyses.

According to Gathercole, Adams, and Hitch (1994), children use spontaneous rehearsal from about age 7. The participants matched with individuals with Down syndrome of this study were younger than 7 years. It is speculated that the failure to obtain a significant difference in recall latency between the DS group and the MA controls can be attributed to the following factors. (a) If spontaneous rehearsal occurs in children older than 7 years, the participants (controls) in the study might not have rehearsed during the digit recall task; this would be consistent with their shorter recall latencies. (b) If rehearsal occurred during the recall latency as assumed, then longer recall duration should have led to a longer digit span. However, the DS group showed longer mean recall latency than the MLU controls but similar digit spans. (c) Alternatively, a few of the individuals in the DS group might have rehearsed vocally or subvocally, with resulting longer recall latency. This may have been the case, but their poorer performance relative to MA controls cannot be attributed to a slower speaking rate.

Language Production Deficit

The language production deficit characteristic of Down syndrome (Chapman, 1995, 1997a, 1997b) was found to be a factor correlated with the verbal short-term memory deficit (Bilovsky & Share, 1965; Das, 1985; McDade & Adler, 1980). The current results of the multiple regression analysis suggest that there is a connection between language production deficit and short-term verbal memory deficit in individuals with Down syndrome.

Language production performance level accounted for a substantial amount of the variance in digit span performance in both the DS and the MLU group. The contribution of recall latency and speaking rate to the variance accounted for in digit span was negligible compared to the contribution of the language production measure. These results suggest an association between the language production deficit and reduced auditory short-term memory performance in individuals with Down syndrome that is not accounted for by speaking rate or longer latencies.

This result, coupled with the lack of significant contribution of either the language production level or the phonological loop measures in the MA controls, suggests that the language production level plays a greater role in the verbal memory span at younger developmental levels. These results are interpreted to mean that the phonological loop is influenced not only by nonverbal cognitive level but also by language production level. Alternatively, in the Baddeley model, the cognitive differences in digit span could arise from specific impairments of the central executive functioning in working memory, rather than the phonological loop. Conners, Carr, and Willis (1998) reported that a difference in digit span was partialled out by measures of central executive functioning in individuals with mild mental retardation. One difficulty in assessing this latter possibility is to find measures of central executive functioning that can be carried out at younger cognitive levels; backward digit span or competing language tasks are typically too difficult for the level of performance among these participants.

Articulatory Rehearsal Deficit

The articulatory rehearsal loop hypothesis was examined by measuring recall latency and speaking rate, given the hypothesis that the faster the speaking rate, the more information can be rehearsed (Henry, 1994;

Henry & Millar, 1991). Individuals with Down syndrome demonstrated no speaking rate deficit in digit span recall. Individuals with Down syndrome failed to show recall latencies different from those of the MA controls. However, individuals with Down syndrome did have longer recall latencies than the MLU controls, and greater variability.

The recall latency of 7 individuals with Down syndrome was longer than 2000 ms (see Figure 1). Their digit span ranged between 3 and 5 digits, which suggests they might have rehearsed to maintain auditory information in the passive phonological store longer than 2 s. The recall latency in the MA and MLU controls was shorter than 2 s across the digit spans. It appears that the control children who participated in the study did not pause long enough to use spontaneous rehearsal during the recall task. If they rehearsed, recall latency might have been longer than 2 s. (A rehearsal duration per digit is expected to be 600 ms, based on a mean average of stimulus duration per digit.) Unfortunately, no systematic observation of overt rehearsal was made in the present study.

Critique of Baddeley's Working Memory Model

There are several unspecified aspects of Baddeley's working memory model (1986, 1992). One is whether the articulatory rehearsal process occurs every time verbal stimuli are presented to the system. If it does not, as the developmental data indicates, what determines the initiation of the articulatory rehearsal process?

The model states that auditory verbal stimuli are registered automatically in the phonological input store within the phonological loop. How, then, do the two components of the phonological loop work? Do the phonological input store and the articulatory rehearsal process work serially or in parallel for auditory verbal stimuli? Several studies have shown that the phonological loop lasts for about 1.5 to 2 s (Baddeley, Thompson, & Buchanan, 1975; Zhang & Simon, 1985), but how the time is distributed to components within the phonological loop is unspecified. A clearer understanding of the working memory model may be facilitated by brain function research as well as language research.

A study (Awh et al., 1996) that used positron emission tomography of normal adults claimed a functional independence (p. 25) between storage and articulatory rehearsal processes in working memory subcomponents. According to the authors, different parts of the brain are activated: anterior regions for articulatory rehearsal and posterior parietal regions for storage, indicating the possibilities of parallel processing.

Cowan's Model

Cowan (1992, 1993, 1994) proposed a model slightly modified from Baddeley's working memory model. In Cowan's model, memory decay is depicted as a process of an alternation of decay and reactivation. Memory decay was assumed to occur during interword pauses during short-term memory performance. By adding a dynamical memory trace decay component, the model can explain recall durations longer than 2 s. Such an explanation would be required for the MA controls with longer digit spans in the current study, whose recall durations were longer than 2 s. Cowan also includes an attention component in his model (1993, p. 163) that would be comparable to central executive functioning.

Clinical Implications

In the auditory memory span task, individuals with Down syndrome performed at the level of language-production-matched controls, rather than at the level of the nonverbal mental-age-matched controls. Clinicians need to recognize the dissociation within both cognitive and linguistic domains reflected in these results. Specific problems in auditory memory span and expressive language development are present in individuals with Down syndrome, relative to other cognitive and comprehension skills.

Limitations of the Present Study

Some of the limitations of the current study are in part related to its retrospective nature. Individuals received different test items because of different basal and ceiling levels in standardized tests. To compensate, maximum performance for each individual (recall performance at the highest lengths of digit span and sentence memory subtests) was used for data analysis. Therefore, no information on within-subject variability was available. This decision also limits some statistical analysis (e.g., Group × Span block interaction) because of unequal n or $n = 0$ for some cells. Nor were observations of overt rehearsal made at the time of test. The present study did not consider potential contributions of executive processes in the model.

The natural speaking rate of individuals with Down syndrome was studied in a recall task. Recall performance was measured without forcing participants to speak as rapidly as possible. Maximum speaking rate in a simpler task than digit recall, such as a diadochokinetic task, may provide valuable information as a replication. This is especially important because of the nonsignificant difference among the groups in speaking rate (digits/s) obtained in the current study.

In the current study only correct recall performance was evaluated. Analysis of temporal measures on incorrect recall performance as well as examination of individual performance at various span lengths might also provide some valuable information to uncover the nature of working memory in individuals with Down syndrome.

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