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Digit Span Changes From Puberty to Old Age Under Different Levels of Education

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The goal of this study is to demonstrate the age-related changes in multimodality digit span under a research design in which level of education is controlled. Volunteer participants ($n = 1183$) were distributed over levels of age (13–98 years) and education (5–8, 9–11, and 12+ years). Digit span was measured through 11 scores of the Visual Aural Digit Span Test–Revised on aural or visual stimulation and oral or written response execution, thus allowing for the measurement of intra- and intersensory integration. The increase in digit span scores reversed to a decrease with early adulthood. The slope of the regression line was small but significant. A $4 \times 3 \times 2$ multivariate analysis of variance showed a significant effect of age and education on a combined score comprising the 11 digit span scores. Differences of age and education were predicted by the auditory and visual input scores. The article discusses the cognitive correlates and the age-related changes in digit span from the biological standpoint.

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Memory span was defined as the maximum number of items that can be perfectly produced following a single presentation (Ebbinghaus, 1913; Jacobs, 1887). In his classical work, Miller (1956) described this limitation as the "magical number" 7, plus or minus 2. The limited span was related to the limits of human information processing and was found to be applicable to a variety of stimuli with respect to absolute judgement, attention, and immediate memory. In the studies that followed, the limited span was demonstrated both in the short-term memory (STM) in the structural model and the phonological loop of the working memory (WM) model (Anderson, 1980; Baddeley, 1990; Baddeley, Logie, Bressi, Della-Sala, & Spinner, 1986; Bryne, 1998; Halford, Maybery, O'Hare, & Grant, 1994).

Span of STM is measured by simple span tests and tests of WM, by complex span tests (Halford et al., 1994). Whereas simple span tests may employ words, letters, shapes, or digits, many of the tests of memory span use digits when assessing the limited-capacity system simply because associative influences are considered to be less for digits than for other types of materials (Dempster, 1981; Lezak, 1995). Thus, span is measured through the digit span in the Wechsler Memory Scale–Revised (WMS–R), a neuropsychological test that measures basic aspects of memory; the Visual Aural Digit Span (VADS) Test, a device presumed to measure STM, sequencing, intra- and intersensory integration; the Serial Digit Learning Test (SDLT), one of the few neuropsychological tests that measure learning capacity; and Wechsler Intelligence Test–Revised (WAIS–R), a test that measures general ability (Koppitz, 1977; Wechsler, 1981, 1987; Zangwill, 1943).

Span of memory may be measured with forward or backward repetition of digits. According to Rosen and Engle (1997), forward and backward recall reflects neither different levels of processing complexity nor different types of representations. Conners, Carr, and Willis (1998) found that forward digit span is related to central executive functioning rather than to phonological loop functioning. However, this relationship has been ascribed to the role of a general speed factor that influences rehearsal; the speed factor is responsible for the variations in both intelligence and span (Kail, 1991). However, in a majority of research, backward repetition of digits were found to load on spatial and transformative elements that represent planning and intelligence rather than the storage capacity that forward repetition of digits are presumed to measure (Griffin & Heffernan, 1983; Ramsay & Reynolds, 1995).

CRITICAL ASPECTS OF DIGIT SPAN

As a measure of human information-processing operation, memory span has been a subject of intensive research (Blankenship, 1938; Dempster, 1981). However, there are a number of issues that still need systematic research attack. WMS–R and WAIS–R are frequently used for measuring digit span; however, in both of these neuropsychological tests, the mode of presentation and mode of response are aural and oral, respectively. The sensory–motor integration is thus always intrasensory. Meanwhile, there is no basis for assuming that material requiring an intrasensory integration is similarly retained in the STM as one that requires an intersensory integration, because the pathways and the centers of the brain involved in the two types of integrations are not identical (Kolb & Whishaw, 1996). However, the literature does not contain a systematic study concerning modality effect on digit span.

Similarly, memory for input from auditory and visual modalities and memory as reflected in oral and written mode of expression may not be similar. In fact, diverse areas of research provide evidence that point to the dissimilarity of these modalities. In line with this, when tasks for each of the two sets of modalities, namely, auditory–visual and oral–written, are performed simultaneously, they do not interfere with each other (Fastenau, Conant, & Lauer, 1998; Frick, 1984; Margrain, 1967; Powell & Hiatt, 1996; Rollins & Hendricks, 1980). This finding shows that memory for acoustically versus optically presented material and memory reflected in written versus spoken material may not be similar. In the field of neuropsychology, the discrete nature of the two sensory modalities is demonstrated in the existence of separate auditory and visual agnosias; the discrete nature of written versus spoken responses are implied in the existence of aphasia versus agraphia, respectively (Kolb & Whishaw, 1996).

Another body of knowledge that points to the differential nature of aural versus visual stimulation and oral versus motor response comes from the literature on learning in elementary school children. Studies demonstrate the existence of individual preferences and differential difficulty in retaining visual or auditory material and in producing material in spoken or written form (Curley & Reilly, 1983; Dean & Rothlisberg, 1983; Koppitz, 1973; Moore, 1986; Rothlisberg & Dean, 1985). A group of findings demonstrated that normal readers were differentiated from the poor readers when the material was presented in the auditory modality (Payne, Davenport, Domangue, & Soroka, 1980; Payne & Holzman, 1983). Another group of findings showed that task structure, namely, the simultaneous versus sequential presentation of the digits in the VADS Test, could be a basis for differentiating good readers from poor ones (Torgesen, Bowen, & Ivey, 1978). The specified studies on children with learning disabilities and the related literature in neuropsychology thus show the necessity of investigating the digit span for not only the aural–oral but also the aural–written, visual–oral and visual–written modalities.

As with most other information-processing operations, memory span changes with age. Age-related changes in digit span has been a subject of interest for a broad spectrum of basic and applied sciences, among which are cognitive psychology, neuropsychology, psychophysiology, educational psychology, and psychogeriatrics (Craik & Jennings, 1992; Hartley, 1992; Salthouse, 1990, 1993; Salthouse & Babcock, 1991; Winocur & Moscowitch, 1984, 1990; Winocur, Moscowitch, & Freedman, 1987). However, a group of these developmental studies investigated only the incremental phase of the digit span (Baddeley, Thomson, & Buchanan, 1975; Dempster, 1981; Hulme, Thomson, Muir, & Lawrence, 1984; McLaughlin, 1963; Miller, 1956; Naveh-Benjamin & Ayres, 1986; Olazaran, Jacobs, & Stern, 1996; Pascual-Leon, 1970; Spring & Capps, 1974). Dempster (1981) summarized the findings of 15 studies that investigated the incremental phase of span; the values had been obtained in these studies from participants who were between 2 years of age and young adulthood (college students). Dempster (1981) reported the findings for different ages by averaging across two or more studies. This review showed a threefold increase of digit span scores in the studied age range. Age-related increases in digit span of elementary school children were also demonstrated in the scores of the VADS Test (Koppitz, 1970, 1977).

A second group of developmental studies investigated the decremental phase of digit span; these studies showed that there was a small but reliable decline in simple span scores during aging (Dobbs & Rule, 1989; Johansson & Berg, 1989; Margolis & Scialfa, 1984; Pacaud, 1989). Salthouse and Babcock (1991) reported two large-scale studies ($n_1 = 227$ and $n_2 = 233$, respectively) in which they explored the effect of age on various span measures. The correlations between age and digit span were found to be $-.34$ and $-.18$ in Studies 1 and 2, respectively. In a large-scale normative study ($n = 1811$ participants) where information-processing operations were comprehensively investigated throughout aging (20–95 years of age); the slowest age-related decrease was found for digit span scores of WMS–R. The slope of the regression line for the total forward digit span score was found to be $-.04$ (Karakaş et al., 1998).

The previously cited studies show that the digit span was not investigated so as to cover the critical ages; a group of studies investigated its incremental phase, and another, the decremental phase. When collectively taken, the studies show that digit span first increases and then decreases. However, these studies fail to show the point at which the increase in digit span reverses to one of decrease.

Further, there is incongruency between the digit span findings of different studies. Although Zagar, Arbit, Stucky, and Wengel (1984) showed the forward digit span decrease to be from 11.27 digits in 20- to 29-year-old adults to 10.03 in 70- to 79-year-old ones, Wechsler (1987) found this decrease to be from 9.0 in 20- to 24-year-old adults to 7.5 in 65- to 69-year-old ones. Karakaş et al. (1998) found this decrease to be from 6.07 in 20- to 34-year-old adults to 5.11 in 55- to 64-year-old ones with less than university education. In participants with university education, the decrease was from 7.71 in 20- to 34-year-old adults to 6.73 in 55- to 64-year-old adults.

METHODOLOGICAL SHORTCOMINGS IN DIGIT SPAN STUDIES

A critical evaluation of the studies on digit span reveals the lack of necessary controls and the ensuing probable contamination. Two of these are the ad lib usage of mnemonic or organizational strategies in storing digits and the effect of education on digit span performance. The instructions in subtests of WMS–R, WAIS–R, and VADS, neuropsychological tests that are prevalently used for measuring digit span, include no limitations regarding the usage of compensatory organizational or mnemonic strategies. However, when confronted with deliberate memory tasks, humans use mnemonic or organizational strategies. These include rehearsal where information in STM is continually articulated or refreshed, chunking where two or more items are recoded into a single familiar unit, and retrieval strategies where items are grouped on the basis of temporal or spatial characteristics (Anderson, 1980; Cowan, Nugent, Elliott, Ponomarev, & Saults, 1999; Dempster, 1981; West, 1995). MacGregor (1987) mathematically showed that beyond five items for exhaustive search and six items for self-terminating search in unorganized memory, grouping the items becomes more efficient. Capacity increase in STM via the usage of mnemonic strategies have specifically been shown for digit span (Chi, 1977; Dempster & Zinkraf, 1982; Feld & Witte, 1988; Huttenlackher & Burke, 1986). When such strategies are used, the digit span score increases even though the capacity of the store may still be the same number of items. When such memory aids are used, what is measured is not, according to Easby-Grave (1924), the "true span."

Another uncontrolled factor in digit span studies is the level of education. The significant effect of education on digit span was documented in a number of studies (Garcia-Morales, Gich-Fulla, Guardia-Olmos, & Pena-Casanova, 1998; Karakaş et al., 1998; Pacaud, 1989). However, even in a widely used test such as the WMS–R, norms were not given for different levels of education. Participants in the normative sample did come from different levels of education but data were collapsed over this variable when calculating the norm values. Similarly, Zagar et al. (1984) studied age-related changes in the WMS scores of 2,045 participants who were between 20 and 79 years. However, even in such a large scale study, no information was provided on the effect of education or how this factor was controlled.

This study is a large-scale investigation of human digit span. The specific aims of the study were to investigate age-related changes in multimodal digit span and whether these changes were dependent on level of education. The general purpose of the study was to gain a more comprehensive understanding of the limitation in human information-processing via the digit span.

METHOD

Participants

The study was conducted on a total of 1,183 participants. Early and late adult participants were reached at governmental or private organizations, and the elderly participants at their dwellings or homes for the elderly. The sample consisted of volunteers who met the following criteria: being equal to or over 13 years of age, having had at least 5 years of schooling (elementary school) and living in an urban area. Other criteria pertained to the general health condition, which included having normal or corrected vision and audition, being free of neurological or psychiatric problems, not using pharmacological drugs that interfere with cognitive function or not having recently stopped taking such drugs. The reliability of self-reports of the 13- to 19-year-old age group was checked through the school administrative records. The reliability of self-reports of the old-old age group were checked through the people that they lived with or were closely associated with them or the medical staff of the institutions where they lived.

Participants were distributed over levels of age, education, and gender. The sample consisted of 175 participants in the puberty stage (13–15 years), 197 participants in adolescence (16–19 years), 256 participants in early adulthood (20–34 years), 224 participants in late adulthood (35–54 years), 202 participants in old age (55–69 years) and 129 participants in old-old age (70–98 years). There were 581 females and 602 males in the sample.

Levels of education were divided into three categories. There were 457 participants who had 5 to 8 years of schooling. This group included the 13- to 15-year-old participants who were, at the time of testing, at various grades of junior high school; the group also included elementary school and junior high school graduates at all other age levels (20–98 years). There were 458 participants who had 9 to 11 years of schooling. This group included the 16- to 19-year-old participants who were, at the time of testing, at various grades of senior high school. The group also included senior high school graduates at all other age levels (20–98 years). Participants in the 13 to 15 and 16- to19-year-old age groups were equally distributed over successive grades of junior high (first to third grades) and senior high (first to third grades) school. There were 268 participants who had 12 years of schooling or more. This group included participants who were undergoing university education at the time of testing. The group also included participants at all age levels (20–98 years) who had at least license degrees.

Apparatus

The Visual Aural Digit Span Test–Revised (VADS–R Test) was based on the VADS Test (Koppitz, 1977). The VADS Test was originally designed as a diagnostic tool for assessing reading and learning disabilities in primary school children (Koppitz, 1977). Some of the procedural aspects of this neuropsychological test may have been appropriate for the specified aims. However, these procedural aspects stand as shortcomings when the aim is to determine the storage capacity, in terms of the number of units, that individuals of all age levels can retain in the limited capacity system. The VADS–R Test was developed to alleviate some of the shortcomings of the original test.

The VADS–R Test measured digit span from a multimodality perspective. In the test, digits were presented through either aural or visual modality, and the response was required in either oral or written form. In the VADS–R Test, each combination of stimulus presentation and response execution formed a different subtest. As with other psychometric tools, the subtests of the VADS–R Test were administred in a standard order (Lezak, 1995; Spreen & Strauss, 1991). The order of administration was as follows: aural–oral (A–O), visual–oral (V–O), aural–written (A–W) and visual–written (V–W).

In the original VADS Test, the items in subtests that involved aural presentation were given by the testor at the rate of one per sec. However, in subtests that involved visual presentation, the card, where all digits of given item were printed, was shown to the participant for 10 sec (Koppitz, 1977). With such a procedure, the time for each digit varied between 3.3 sec for a three-digit item (10/3) to 1.43 sec for a seven-digit item (10/7). In the VADS Test, the rate for aural and visual presentation was thus not held constant. Due to these differences in the method of presentation, time entered as a confounding variable. Further, with such a methodology, the visual material was presented simultaneously whereas the aural material was presented successively. Thus, order had to be reconstructed when the material was presented in the auditory modality and only to be identified when it was presented in the visual modality.

The stimulus presentations that were developed for the VADS–R Test ensured an identical presentation rate and also successive mode of processing for the auditory and visual input. In subtests with aural presentation, consecutive items were printed on two different cards, one for each trial. The consecutive digits in a given item were read aloud at the rate of one per second by the testor. Subtests with visual presentation used two separate booklets, one for each trial. The booklets contained partition cards that separated the items. The number of digits in the following item was specified on these cards, discernible only to the testor. The numbers in the visual presentation booklets were printed as Arabic numerals (as 1, 2, 3, etc.); the font type was Helvetica and font size was 51 mm. The consecutive digits in a given item were shown to the participant at the rate of one per second, each printed on consecutive pages of a booklet.

The longest series in the original VADS Test had included seven digits. Because Koppitz (1977) reported a ceiling effect in some of the fifth graders, two new items, respectively including eight and nine digits, were added to each subtest of the VADS–R Test. Testing started with the two-digit item. The participant was asked to respond in the appropriate modality 1 sec after the presentation of the last digit of a given item. In the oral response mode, the participant was asked to repeat the series aloud; in the written response mode, the participant was asked to write the digits on an A4-size paper. If the participant successfully reproduced all digits of the given item in their correct order in the first trial set, the next item in the first set that was one digit longer than the previous was presented. If the participant was not successful at the first trial, the item in the second trial set was presented that had the same number of digits. If the participant was successful in the second set, testing continued with the next longer item in the first set. If not, testing was terminated.

The scores in the VADS–R Test were based on the number of digits in the longest series that could be correctly reproduced by the participant. VADS–R Test yielded 11 scores. The subtests yielded four basic scores; each score varied between 0 and 9. Combinations of subtest scores yielded six combination scores; these scores varied between 0 and 18. The total score varied between 0 and 36. The basic scores were A–O, V–O, A–W, and V–W. The combination scores were aural input (AI) score (A–O + A–W), visual input (VI) score (V–O + V–W), oral expression (OE) score (A–O + V–O), written expression (WE) score (A–W + V–W), intrasensory integration (INTRA) score (AO + VW), intersensory integration (INTER) score (VO + AW) and total (TOTAL) score (AO + VO + AW + VW).

The VADS–R Test was administered individually under standard instructions. These included general instructions that were given at the commencement of test administration and subtest-specific instructions that were given before each subtest. The instructions required the participant to learn and to recall the digits singly and not to use mnemonic or organizational strategies. These standard instructions were another revision that was included in the VADS–R Test.

Reliability and validity of the VADS–R Test. The reliability of the VADS–R Test was studied in 36 volunteer participants who were equally distributed over levels of age (13–19 years), gender, and grades. The participants were from three different types of high schools, namely private schools, state schools with entrance examinations, and state schools without entrance examinations. The reliability of the VADS–R Test was estimated with the test–retest technique. Time interval between the two testings was 15 days. The reliability coefficient for the representative VADS–R Test TOTAL score was found to be .84 at the $p < .001$ level of significance.

The criterion validity of VADS–R Test was studied on a second sample of 36 volunteer participants who were also equally distributed over levels of age (13–19 years), gender, and grades. As with the reliability study, the participants were from three different types of high schools. The participants were recruited from the above specified high schools. The participants were first administered the VADS–R Test, and after 15 days the WAIS–R, Benton Visual Retention Test, and D2 Visual Attention Test. The tests were administered to each participant in a different random order.

The highest correlation coefficient ($r = .69$, $p < .001$) was obtained between the VADS–R scores and the analogous WAIS–R digit span scores, which were obtained with forward repetition of digits (D–F). Meanwhile, the correlation coefficients between total score of the VADS–R Test and the arithmetic score of the WAIS–R was 0.45 ($p < .001$). The pattern of correlation among different tests were also studied using the D2 Test, a psychometric tool that measures speed and accuracy of visual discrimination (Brickenkamp, 1981). The pattern of correlations between the VADS–R Test and D2 scores ranged between 0.23 ($p < .05$) and -0.28 ($p < .001$). The correlations between the VADS–R Test and either the Benton Visual Retention Test scores or the WAIS–R Digit Symbol scores were not found to be significant.

Principal components extraction with varimax rotation was performed on the VADS–R Test, WAIS–R, Benton Visual Retention Test, and D2 Visual Attention Test scores. Principal components extraction was performed prior to principal factors extraction to estimate number of factors, presence of outliers, absence of multicollinearity, and factorability of the correlation matrices. Five factors were extracted, explaining 79.78% of the variance. With a cutoff of .45 (20% of variance) for inclusion of a variable (scores) in interpreting a factor, all VADS–R scores and the digit span scores of the WAIS–R loaded on the first factor with loadings between .71 and .99.

Another validation study (Genç-Açıkgöz, 1995) was conducted on university students ($n = 140$) who had a mean age of 22.4 years. Among a battery of tests that included the WMS–R, Auditory Visual Learning Test (AVLT), and SDLT, VADS–R; A–O scores showed the highest correlation (0.34) with the digit span scores of the WMS–R. A third validity study was carried on adults who were between 20 and 74 years of age (Karakaş, Eski, & Başar, 1996). Factor extraction was achieved using principal components analysis. The cumulative percentage for all factors with eigenvalues greater than one was found to be 83.78. All VADS–R scores and the WMS–R digit span scores (forward repetition, backward repetition, and total score) loaded on the first two factors. These factors explained 41.53% of the variance, and the factor loadings varied between .61 and .96. All other scores of the WMS–R were distributed under the remaining factors.

Procedures

Testing was accomplished by trained testors. Test administration was performed at schools for participants at puberty or adolescence stages, at governmental or private organizations for early and late adult participants, and at homes or institutions for the elderly participants. Care was taken to maintain optimal conditions of testing.

Data collection started with the administration of the standard Recording Form that was specifically prepared for this study. The Recording Form included questions on the demographic and the health status of participants. The information given by the elderly participants with respect to health and drug usage was checked through people who were closely connected to the elderly. Following this, VADS–R subtests were administered in their standard order. During test administration, the tester observed the behavior and the cognitive, emotional and motivational state of the participant. Relevant recordings were made on the Recording Form after the participant left the testing environment.

RESULTS

Normative Data (13–98 years of age) for Digit Span

Table 1 presents normative data on the TOTAL and the A–O score of the VADS–R Test. The data were grouped under six levels of age, three levels of education, and two levels of sex. The age groups were adapted from the WAIS–R and WMS–R to allow comparison of VADS–R digit span with those reported for the WAIS–R and WMS–R (Wechsler, 1981, 1987).

Table 1 showed that within given levels of education, TOTAL and A–O scores decreased as age increased. Within given levels of age, scores increased as level of education increased. The difference in digit span scores due to gender difference was not not appreciable. Parallel findings were obtained for the remaining VADS–R scores under levels of age, education, and gender.

Figure 1 shows the age-related changes in TOTAL score of the VADS–R Test. The studied age range was between 13 and 98 years. The level of education was kept at 5 to 8 years, because this was the level that could have been possible for the 13- to 19-year-old age group. The VADS–R scores yielded three different maxima: 9 for the basic scores, 18 for the combination scores, and 36 for the total score. To facilitate comparison, the scores were transformed to the *z* distribution. The *z* transformations were performed according to the formula where the standard deviations and the number of participants for each specific combination of conditions and for the total group comprising of all combinations were separately entered into the equation. Figure 1 shows that all measures of digit span increased throughout 13 to 19 years of age; the scores peaked at this level, whereafter they systematically decreased until old-old age. The smaller graph in Figure 1 zooms at the increase, turning point, and decrease of the scores. Fine partitioning of the age variable between 16 to 20 years of age demonstrated that the reversal point of digit span scores was at 18 years of age. As is demonstrated in Figure 2, a quadratic (second order) model best fit the data (constant = 28.103; $b_1 = -.240$, $SE\ b_1 = .029$, $p < .001$; $b_2 = .001$, $SE\ b_2 = .00$, $p < .001$). In linear regression analysis, the slope of the regression line was found to be 0.5 for the 13- to 19-year-old age group (intercept = 16.76, $SE = 1.7$, $p < .001$) and -0.03 for the 20- to 98-year-old age group (intercept = 19.61, $SE = .59$, $p < .001$).

Distribution of Digit Span Scores

Figure 3 shows the line graphs of frequency of occurrence of the basic VADS–R scores for participants from 20 years of age on ($n = 811$). The data were collapsed over levels of age and education. The figure demonstrated the similarity of the frequency distribution for the four basic digit span scores. For all basic scores, the

TABLE 1
Means and Standard Deviations of the VADS–R Total Score and Aural–Oral Score as a Function of Age and Education

		Education					
		5–8 Years		*9–11 Years*		*12 Years and Above*	
Age		*Female*	*Male*	*Female*	*Male*	*Female*	*Male*
13 to 15 years	*n*	85	90				
Total	*M*	23.41	24.66				
	SD	3.46	3.60				
A–O	*M*	5.81	6.17				
	SD	1.18	1.21				
16 to 19 years	*n*			97	100		
Total	*M*			25.34	25.98		
	SD			4.0	3.62		
A–O	*M*			6.30	6.40		
	SD			1.24	1.02		
20 to 34 years	*n*	32	44	47	40	51	40
Total	*M*	18.09	19.27	23.04	24.13	24.43	24.53
	SD	2.45	3.07	3.50	3.63	3.88	3.32
A–O	*M*	5.09	4.93	5.81	6.20	6.06	5.98
	SD	1.06	1.21	1.12	1.02	1.14	1.00
35 to 54 years	*n*	41	43	34	35	36	35
Total	*M*	16.15	17.70	22.09	22.26	23.56	23.71
	SD	3.21	3.03	3.55	3.56	3.80	3.71
A–O	*M*	4.32	4.58	5.47	5.57	5.69	6.00
	SD	.85	.98	.93	1.20	1.19	1.03
55 to 69 years	*n*	36	40	30	36	30	30
Total	*M*	15.25	15.75	19.63	18.97	22.13	20.93
	SD	2.58	3.21	3.85	3.79	2.76	2.96
A–O	*M*	3.92	4.13	5.17	5.00	5.47	5.13
	SD	.73	.97	.99	1.20	1.04	1.07
70 and above	*n*	23	21	20	19	17	29
Total	*M*	14.78	15.38	17.90	17.95	19.94	20.17
	SD	3.19	2.71	2.13	2.55	2.93	3.79
A–O	*M*	3.87	4.10	4.70	4.79	4.94	5.28
	SD	.97	1.04	.73	.79	.83	1.25

Note. VADS–R = Visual Aural Digit Span–Revised; A–O = Aural–Oral.

median was 5.0. The mode was also 5.0 for all basic scores but V–W, where it was 4.0. The means varied from 4.77 to 5.16 (for V–O and A–O, respectively). The distribution of the scores was best approximated by the gamma distribution. (The analysis was carried under Bestfit.)

The percentages of the highest digit span score, 9, for A–O, V–O, A–W, and V–W subtests were found as 1.1, 0.9, 0.9, and 3.0, respectively, for the total

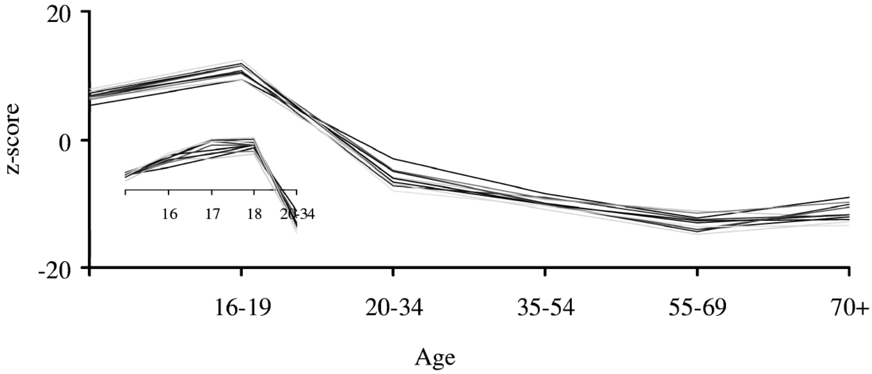

FIGURE 1 The effect of age (13 to 70+ years) on the 11 Visual Aural Digit Span–Revised scores in participants with 5 to 8 years of education.

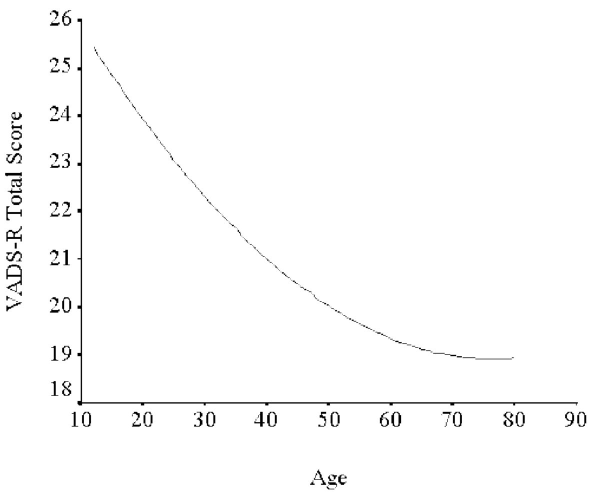

FIGURE 2 The quadratic polynomial model, where age was the predictor variable and the Visual Aural Digital Span–Revised total score was the predicted variable.

population. For the same subtests, the percentage of the next highest score, 8, were 2.0, 1.4, 3.0, and 6.3. However, only 1 participant in the total sample had the maximum score of 9, 9, 9, 9 and in all subtests. One participant scored 9, 9, 9, 8; and 6 participants, scored 9, 9, 8, 8; and 2 participants scored 9, 8, 8, 8. Of these 10 participants, all but 1 was from the 13- to 19-year-old age group. These 10 participants comprised 0.84% of the total population. These findings demonstrate that

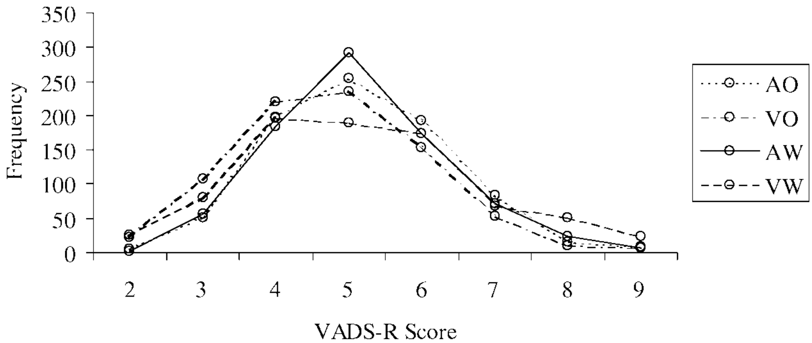

FIGURE 3 The frequency distribution of the basic VADS-R scores.

the extension of the number of digits to nine sufficiently covers the digit span of the 13- to 98-year-old year age group when the span is obtained under the instructions of the VADS–R Test.

The Effect of Age, Education, and Gender on Scores of the VADS–R Test: Multivariate Analysis of Variance

Findings for participants in the 20 to 98 age range. Table 2 demonstrates the correlation matrix between age and the 11 VADS–R scores; the table shows that the bivariate correlations between the 11 scores were between .52 and .95 ($p > .01$). The magnitude of the correlations warranted the usage of multivariate analysis techniques for studying the pattern of multivariate relations between the scores.

Principal factors extraction with varimax rotation was performed on the 11 scores. Principal components extraction was performed prior to principal factors extraction to estimate the number of factors, presence of outliers, absence of multicollinearity, and factorability of the correlation matrices. One factor was extracted explaining 83.37% of the variance. The communality values for variables were 1.00, showing that the variations were well defined with this factor structure. With a cutoff of .45 (20% of variance) for inclusion of a variable (score) in interpreting a factor, all variables loaded on the same factor. The factor loadings ranged from .83–.99. This factor structure, where many variables loaded on the same factor with high values, showed that the variables, that is, the VADS–R scores, were homogeneous.

A 4 × 3 × 2 (age, education, and gender) multivariate analysis of variance (MANOVA) was performed on dependent variables (DV) consisting of the

TABLE 2
Intercorrelations Between Age and VADS-R Scores*

Variables	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
1. AGE	—	–.30	–.39	–.34	–.39	–.36	–.43	–.40	–.42	–.40	–.42	–.44
2. A–O		—	.55	.63	.52	.90	.59	.87	.64	.84	.67	.80
3. V–O			—	.60	.64	.61	.89	.89	.68	.69	.89	.83
4. A–W				—	.57	.91	.62	.63	.86	.68	.88	.83
5. V–W					—	.61	.92	.66	.91	.90	.69	.85
6. AI						—	.67	.85	.84	.84	.86	.90
7. VI							—	.84	.89	.88	.86	.92
8. OE								—	.75	.87	.89	.93
9. WE									—	.90	.87	.94
10. INTRA										—	.78	.95
11. INTER											—	.94
12. TOTAL												—

Note. VADS–R = Visual Aural Digital Span–Revised; A–O = aural–oral; V–O = visual–oral; A–W = aural–written; V–W = visual–written; AI = aural input; VI = visual input; OE = oral expression; WE = written expression; INTRA = intrasensory; INTER = intersensory.
*All correlation values are significant at $p < 0.01$.

VADS–R scores. The combination scores were given the first priority, followed by the total score and later by the basic scores. The order of entry was thus as follows: AI, VI, OE, and WE, INTRA, INTER, TOTAL, A–O, V–O, A–W, and V–W. Two scores, V–O and V–W, were found to be linearly dependent on the preceding scores, leading to a singularity of the within-cells error matrix. These scores were left out, and the analyses were carried out on the remaining nine VADS–R scores.

The independent variables (IV) were age (20–34, 35–54, 55–69, 70–98), education (5–8, 9–11, and 12 years and above) and gender (male, female). In the analyses, sequential adjustment was made for nonorthogonality. Order of entry of IVs were age, education, and then gender. There were no missing cases. There were no univariate or multivariate within-cell outliers. Tests concerning the assumptions of normality, homogeneity of variance–covariance matrices, linearity, and multicollinearity were found satisfactory.

With the use of Wilk's criterion, the combined DVs were significantly affected by age, $F(27, 2275) = 9.04$, $p < .001$, education, $F(18, 1558) = 26.68$, $p < .001$ and gender, $F(9, 779) = 2.28$, $p < .01$. All interactions were also found significant at least at $p < .01$. The strength of the association was highest between education and the combined DVs ($\eta^2 = .38$). The strength of association between age and combined DVs was moderate ($\eta^2 = .26$).

To investigate the impact of each main effect on the individual DVs, a stepdown analysis was performed on the prioritized DVs. All DVs were judged to be sufficiently reliable to warrant stepdown analysis. In stepdown analysis, each DV was analyzed, in turn, with the higher priority DVs treated as covariates and with the highest priority DV tested in univariate analysis of variance (ANOVA). Homogeneity of regression was achieved for all components of the stepdown analysis. A Bonferroni-type adjustment was made for inflated Type 1 error, and an experimentwise error of 1% was achieved by the apportionment of alphas. The adjusted alpha values are shown in the last column of Table 3.

Two DVs made unique contributions to the composite DV that best distinguished levels of age. A unique contribution to predicting differences between age levels was made by AI, stepdown $F(3, 787) = 54.38, p < .001$. After the pattern of differences measured by AI was entered, a difference was also found on VI, stepdown $F(3, 786) = 14.50, p < .001$. Univariate analyses revealed that each of the remaining VADS–R scores also distinguished levels of age; however, these differences were already accounted for in the composite DV by the two higher priority DVs, namely, AI and VI (for details, see Table 3).

The same two DVs made unique contributions to the composite DV that best distinguished levels of education. A unique contribution to predicting differences among levels of education was made by AI, stepdown $F(2, 787) = 135.43$, $p < .001$. After the pattern of differences measured by AI was entered, a difference was also found on VI, stepdown $F(2, 786) = 64.32, p < .001$. Univariate analyses revealed that each of the remaining scores also distinguished levels of education; however, each of these differences were already accounted for in the composite DV by the two higher priority DVs (for details, see Table 3).

None of the DVs made a contribution to the composite DV for distinguishing levels of gender. After the pattern of differences measured by the eight higher priority DVs was entered, A–W made a unique contribution to the composite DV that best distinguished levels of age by education interaction, stepdown $F(6, 787) = 3.76, p < .001$.

As these data show, selected VADS–R scores are affected by age and education. The greatest contribution to the composite DV that best distinguished levels of age and education were made by AI, the highest priority DV and VI, the DV that had been assigned second place in the priority ranking.

A $4 \times 3 \times 2$ between-subjects MANOVA was also performed where by the TOTAL score was taken from its seventh position and, assigning the highest priority, entered first, followed by the combination and basic scores. With the use of Wilk's criterion, the combined DVs were significantly affected by age, $F(27, 2275) = 9.04$, $p < .001$, education $F(18, 1558) = 23.68$, $p < .001$, and gender, $F(9, 779) = 2.28, p < .05$. All interactions were also found significant at least at $p < .01$. However, in these analyses, a unique contribution to predicting differences was made only by the TOTAL score among levels of age, stepdown $F(3, 787) = 71.56, p < .001$, and levels of education, stepdown $F(2, 787) = 213.59, p < .001$. The two combination scores, AI and VI no longer made unique contributions to predicting differences between levels of age and education.

TABLE 3
Univariate and Multivariate Tests of Age, Education, and Gender and Their Interaction on Adult Participants (20–98 Years of Age), With VADS–R Scores as Dependent Variables

Source	*DV*	*Univariate F*	*df*	*Stepdown F*	*df*	α
Age (A)	A–I	54.38*	3/787	54.38**	3/787	0.001
	V–I	56.90*	3/787	14.50**	3/786	0.001
	O–E	52.14*	3/787	.38	3/785	0.001
	W–E	61.86*	3/787	1.42	3/784	0.001
	INTRA	67.18*	3/787	1.62	3/783	0.001
	INTER	50.78*	3/787	2.51	3/782	0.001
	TOTAL	71.56*	3/787	3.08	3/781	0.001
	A–O	41.10*	3/787	2.97	3/780	0.001
	A–W	39.08*	3/787	2.47	3/779	0.001
Education (B)	A–I	135.43*	2/787	135.43***	2/787	0.001
	V–I	201.89*	2/787	64.32***	2/786	0.001
	O–E	178.53*	2/787	1.58	2/785	0.001
	W–E	169.81*	2/787	1.23	2/784	0.001
	INTRA	172.35*	2/787	2.62	2/782	0.001
	INTER	186.94*	2/787	1.58	2/782	0.001
	TOTAL	213.59*	2/787	2.12	2/781	0.001
	A–O	96.49*	2/787	1.99	2/780	0.001
	A–W	108.09*	2/787	3.13	2/779	0.001
Sex (C)	A–I	1.10	1/787	1.10	1/787	0.001
	V–I	1.66	1/787	.71	1/786	0.001
	O–E	.58	1/787	.61	1/785	0.001
	W–E	1.71	1/787	1.84	1/784	0.001
	INTRA	3.41	1/787	2.38	1/781	0.001
	INTER	.33	1/787	2.64	1/781	0.001
	TOTAL	1.66	1/787	1.37	1/781	0.001
	A–O	1.67	1/787	3.69	1/780	0.001
	A–W	.18	1/787	6.05	1/779	0.001
A × B	A–I	.62	6/787	.62	6/787	0.001
	V–I	2.47**	6/787	2.02	6/786	0.001
	O–E	1.21	6/787	1.14	6/785	0.001
	W–E	1.75	6/787	1.31	6/784	0.001
	INTRA	1.73	6/787	1.51	6/786	0.001
	INTER	1.80	6/787	2.18	6/786	0.001
	TOTAL	1.89	6/787	1.59	6/786	0.001
	A–O	.78	6/787	2.76	6/780	0.001
	A–W	.87	6/787	3.76***	6/779	0.001
A × C	A–I	1.79	3/787	1.79	3/787	0.001
	V–I	2.25	3/787	3.68	3/783	0.001
	O–E	.76	3/787	.73	3/785	0.001
	W–E	1.91	3/787	1.77	3/784	0.001

(*continued*)

TABLE 3 (*Continued*)

Source	*DV*	*Univariate F*	*df*	*Stepdown F*	*df*	α
	INTRA	1.67	3/787	.55	3/783	0.001
	INTER	1.04	3/787	2.22	3/783	0.001
	TOTAL	1.47	3/787	1.07	3/783	0.001
	A–O	1.03	3/787	2.68	3/780	0.001
	A–W	1.62	3/787	4.09	3/779	0.001
B × C	A–I	.77	2/787	.77	2/787	0.001
	V–I	2.46	2/787	1.74	2/782	0.001
	O–E	.54	2/787	1.37	2/785	0.001
	W–E	2.49	2/787	.82	2/784	0.001
	INTRA	1.13	2/787	.51	2/782	0.001
	INTER	2.45	2/787	3.48	2/782	0.001
	TOTAL	1.99	2/787	3.77	2/782	0.001
	A–O	.09	2/787	3.31	2/780	0.001
	A–W	1.94	2/787	2.95	2/779	0.001
A × B × C	A–I	.57	6/787	.57	6/787	0.001
	V–I	.16	6/787	.49	6/786	0.001
	O–E	.82	6/787	1.08	6/785	0.001
	W–E	.08	6/787	1.15	6/784	0.001
	INTRA	.28	6/787	.74	6/786	0.001
	INTER	.26	6/787	2.69	6/786	0.001
	TOTAL	.23	6/787	2.82	6/786	0.001
	A–O	1.03	6/787	2.72	6/780	0.001
	A–W	.43	6/787	2.48	6/779	0.001

Note. VADS–R = Visual Aural Digit Span–Revised; DV = dependent variables; A–I = aural–input; V–I = visual–input; O–E = oral–expression; W–E = written–expression; INTRA = intrasensory; INTER = intersensory; A–O = aural–oral; A–W = aural–written.

*Significance level cannot be evaluated but would reach $p < .001$ in univariate context. **Significance level cannot be evaluated but would reach $p < .05$ in univariate context. ***$p < .001$.

Results on the latter MANOVA showed that when the TOTAL score was entered in the first position, it replaced the two combination scores. After the pattern of differences measured by this score was entered, the combination scores no longer made a contribution to predicting differences between levels of age and education. That is, only the TOTAL score made a contribution to predicting differences between levels of age and education.

Findings for participants in the 13 to 19 age range. A 2 × 2 (age, gender) between-subjects MANOVA was performed on DV consisting of the VADS–R scores. As with the 20- to 98-year-old age group, the combination scores were given first priority, followed by the total score and later by the basic scores. The order of entry was thus as follows: AI, VI, OE, and WE, INTRA, INTER, TOTAL, A–O, V–O, A–W, and V–W. Seven scores (WE, INTER, TOTAL, A–O, V–O, A–W, and V–W) were found to be linearly dependent on the preceding scores, leading to a singularity of the within-cells error matrix. These scores were left out, and the analyses were carried out on the remaining four VADS–R scores.

The independent variables (IV) were age (13–15 and 16–19) and gender (male, female). In the analyses, sequential adjustment was made for nonorthogonality. The order of entry of IVs was age and gender. There were no missing cases. There were no univariate or multivariate within-cell outliers. The results of evaluation of assumptions of normality, homogeneity of variance–covariance matrices, linearity, and multicollinearity were satisfactory.

With the use of Wilk's criterion, the combined DVs were significantly affected by age, $F(4, 365) = 5.54, p < .001$, and gender, $F(4, 365) = 4.14, p < .01$. Age by gender interaction was not found significant. The strength of the association between age and the combined DVs was $\eta^2 = .26$, and that between gender and combined DVs, was $\eta^2 = .03$.

To investigate the impact of each main effect on the individual DVs, a stepdown analysis was performed on the prioritized DVs. All DVs were judged to be sufficiently reliable to warrant stepdown analysis. In stepdown analysis, each DV was analyzed, in turn, with the higher priority DVs treated as covariates and with the highest priority DV tested in univariate analysis of variance. Homogeneity of regression was achieved for all components of the stepdown analysis. A Bonferroni-type adjustment was made for inflated Type I error, and an experimentwise error of 5% was achieved by the apportionment of alphas. The adjusted values are shown in the last column of Table 4.

Two DVs made unique contributions to the composite DV that best distinguished levels of age. A unique contribution to predicting differences between age levels was made by AI, stepdown $F(1, 368) = 8.37, p < .01$. After the pattern of differences measured by AI was entered, a difference was also found on VI, stepdown $F(1, 367) = 12.79, p < .001$. Univariate analyses revealed that the remaining two scores also distinguished levels of age; however, these difference were already accounted for in the composite DV by the two higher priority DVs (for details, see Table 4).

Only one DV made a unique contribution to the composite DV that best distinguished levels of sex. A unique contribution to predicting differences between levels of sex was made by VI, stepdown $F(1, 367) = 11.09, p < .001$. Univariate analyses revealed that two other remaining scores also distinguished levels of gender; however, these differences were already accounted for in the composite DV by the higher priority DV (for details, see Table 4). None of the DVs made a contribution to the composite DV to distinguish levels of Age × Gender interaction.

TABLE 4
Univariate and Multivariate Tests of Age, and Gender and their Interaction on Participants from Puberty and Adolescence Stages (13–19 Years of Age) With VADS–R Scores as Dependent Variables

Source	*DV*	*Univariate F*	*df*	*Stepdown F*	*df*	α
Age (A)	A–I	8.37**	1/368	8.37***	1/368	.01
	V–I	21.35*	1/368	12.79****	1/367	.01
	O–E	16.42*	1/368	.42	1/366	.001
	INTRA	17.41*	1/368	.38	1/365	.001
Sex (B)	A–I	1.04	1/368	1.04	1/368	.01
	V–I	11.13*	1/368	11.09****	1/367	.01
	O–E	9.22**	1/368	3.66	1/366	.001
	INTRA	6.81**	1/368	.67	1/365	.001
A × B	A–I	1.64	1/368	1.64	1/368	.01
	V–I	.01	1/368	.54	1/367	.01
	O–E	.20	1/368	.35	1/366	.001
	INTRA	.75	1/368	.18	1/365	.001

Note. VADS–R = Visual Aural Digit Span–Revised; DV = dependent variables; A–I = aural–input; V–I = visual–input; O–E = oral–expression; INTRA = intrasensory.
*Significance level cannot be evaluated but would reach $p < .001$ in univariate context. **Significance level cannot be evaluated but would reach $p < .01$ in univariate context. ***$p < .01$. ****$p < .001$.

Effect of Strategy Usage on Digit Span Scores

Figure 4 shows the A–O score of the VADS–R and the D–F score of the WMS–R (Karakaş & Başar, 1993), respectively. The A–O score was analogous to the WMS–R D–F score in stimulus presentation and response execution; both tests used the A–O modality. However, the A–O scores represented digit span without the use of mnemonic–organizational strategies, whereas the D–F score represented digit span with their ad lib usage. Curves were plotted as a function of age (20–69 years) for two levels of education (5–8 years and 12 years and above). Because the maximum attainable scores in A–O and D–F were not identical, the scores were *z*-transformed according to the formula described for Figure 1.

Figure 4 showed that for both A–O and D–F scores, participants with 5 to 8 years of schooling had lower scores than participants with a schooling of 12 years or above. A–O scores showed a systematic age effect; there was a linear decrease throughout age levels for both education groups. Linear regression analyses were performed for each specified level of education. The lines were fitted by the method of least squares. Age was the predictor variable, and digit span scores (A–O or D–F) were the predicted variables. Results from the regression analyses supported the observations from

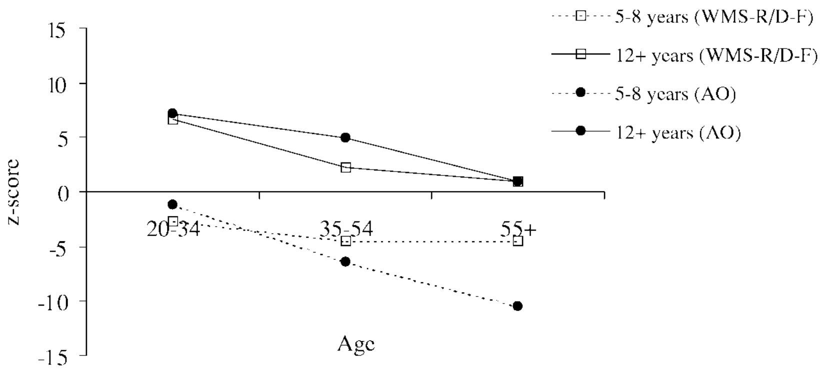

FIGURE 4 The effect of age on digit span measured through the aural–oral (closed circles) and Wechsler Memory Scale–Revised D–F scores (open squares). Data presented for schooling of 5 to 8 years (discontinuous line) and 12 years and above (continuous line). (Data for WMS–R D–F scores are from Karakaş & Başar, 1993.)

Figure 4. For both levels of education, slope of the line for the A–O score was .01, and standard error of the estimate was .01 ($p < .01$). The intercept on the ordinate for the A–O score was 5.21 and 6.39 for 5 to 8 and 12+ years of schooling, respectively. The analogous WMS–R D–F score also kept decreasing until old age (for 5–8 years: $\beta = .04$, intercept = 7.23, $SE = .01$, $p < .01$; for 12 years and above they were: $\beta = .04$, constant = 8.19; $SE = .01$, $p < .001$).

DISCUSSION

This study was on age-related changes in digit span. One characteristic of this study was its multimodal approach to the assessment of digit span, which was measured in this study on auditory or visual input and oral or written expression, thus making both intersensory and intrasensory integration possible. Another characteristic of the study was related to the controls that were imposed on data collection. In this context, the study took the effect of education into consideration. Digit span was measured without the ad lib usage of mnemonic–organizational strategies. Ceiling effect was avoided by using longer digit series and, through the VADS–R Test, digit span was measured under standard instructions.

Many Digit Spans or One?

In his early review article, Blankenship (1938) proposed that different spans are secured depending on the senses through which impressions are received;

accordingly, memory span for each sense organ should be modality specific. Using the VADS Test, Koppitz (1977) studied whether there are differences in digit span when obtained under different modalities of stimulus presentation (auditory and visual input), of response execution (oral and written expression), and stimulus–response integration (inter- and intrasensory). The original VADS Test included 11 different scores, and the manual of the test provided clinical observations that justified the separate usage of these scores (Koppitz, 1977). Other studies on children with learning disability, on normal and poor readers, and on adult clinical samples were focused on the processing of only the auditory and visual input modalities. The findings of these studies pointed to the existence of two separate stores for auditory and visual tasks (Curley & Reilly, 1983; Dean & Rothlisberg, 1983; Frick, 1984; Moore, 1986; Payne et al., 1980; Payne & Holzman, 1983; Rothlisberg & Dean, 1985). Although there are data from tests across modalities on clinical samples, there is little information on the effect of modality on digit span in "normal" samples. Conant et al. (1999) found modality specificity among 6.1- to 12.8-year-old Zairian children, supporting the theoretical distinction between verbal and visual memory span. Powell and Hiatt (1996) showed the separate processing operations of visual and auditory digit span on the basis of forward and backward recall; backward visual digit span was found to be higher than that for backward auditory span. Further, mean number of digits was higher when visual digit span was preceded by auditory digit span. This trend was also observed in normal reading children; however, poor readers performed significantly worse when the first task was presented in the auditory modality (Payne et al., 1980).

This study used a methodologically revised version of the VADS Test; it was conducted on a large sample (n = 1,183), where healthy participants were distributed over levels of age, education, and gender. Multiple scores were analysed with MANOVA to defend data against inflated Type 1 error. The findings of the study showed that, regardless of the age group (13–19 and 20–98), significant differences among levels of age were represented by two combination scores, namely AI and VI. Further, the significant differences between levels of education were represented by the same two scores. The findings of this study thus confirm the existence of separate stores, auditory and visual, over a major portion of the life span (13 years of age onward). Further, this distinction is preserved over different levels of education.

The earlier findings show that digit span does not have 11 different facets, as Koppitz (1977) assumed when she developed the VADS Test. However, the A–O measure of digit span, and thus the auditory store that WMS–R and WAIS–R measure, is not sufficient for representing the memory span for digits. According to this study, the digit span of individuals of both the 13 to 19 and the 20 to 98 age groups should be measured using a psychometric device such as the VADS–R Test, through which the scores for aural and visual modalities can be separately calculated.

Digit Span Changes That Occur Throughout Development

Using the major part of the life span that covers 13 to 89 years of age, this study demonstrated both the incremental and decremental phases of digit span. Irrespective of how the digit span was measured, the incremental phase of the digit span took place between 13 and 19 years of age (Figure 1). Using the original VADS Test, Koppitz (1970, 1977) had observed age-related increases in digit span throughout the various grades of the elementary school. Dempster's (1981) review of the literature also showed that dramatic span increase continued until young adulthood (college). An earlier review by Blankenship (1938) reports findings that locate the maximal span scores at different ages between 12 years to maturity. In line with these findings, this study showed that of the 10 participants who obtained the highest digit span scores, (combinations of 8 and 9 from the four basic subtests) 9 were from the 13- to 19-year-old age group.

The decremental phase of the digit span started at the 20 to 34 age level, and the systematic decrease continued throughout the succeeding age levels. The present study used 11 measures of digit span. MANOVA demonstrated that for the 20 to 98 age group, the effect of age on a "combined" measure of digit span and the strength of association between age and this combined measure was moderate but significant. This finding is in line with the literature where predictability of digit span scores from age was found to be low but significant (Dobbs & Rule, 1989; Karakaş et al., 1998; Pacaud, 1989; Salthouse & Babcock, 1991; Wechsler, 1987; Zagar et al., 1984).

A within-cell analysis of the 16 to 19 age group showed that the reversal point of digit span capacity is at 18 years of age. The finding that the reversal point of digit span was at the end of the adolescence period is a contribution to the literature. Previous research was focused on either the incremental or the decremental phases of digit span; with such a research strategy, the location of the reversal point had naturally not been possible (Dempster, 1981; Dobbs & Rule, 1989; Karakaş, et al, 1998; Koppitz, 1970, 1977; Margolis & Scialfa, 1984; Salthouse & Babcock, 1991; Pacaud, 1989; Wechsler, 1987; Zagar et al., 1984).

The reversal point at 18 years of age may be interpreted in a number of ways. It has consistently been shown that digit span does decrease with age; albeit slight, the decrease is significant. Meanwhile, if, in a given study, development of the digit span is not systematically investigated over a span of critical ages (namely between puberty and young adulthood), the point of maximal digit span can not be observed. Under such conditions, it is hard to tell whether ages in young adulthood are related to an unaltered or even decreasing digit span. Definitionally, the age at which maximal digit span occurs is the point where digit span ceases to develop; mathematically speaking, the rest of the span is the deceleration phase. This is especially so in view of the fact that the increase is dramatic in the incremental phase.

The maximal point of digit span is closely related, biologically, to the development of the frontal lobe, specifically that of the prefrontal cortex (PFC). Postmortem studies, pediatric neuroimaging studies, and electrophysiological studies on both humans and nonhuman primates demonstrate that PFC is one of the last brain regions to mature. Such studies show that the maturational process and the concomitant development of attention and the various forms of memory finalizes, basically through the elimination of excess synapses, between childhood and late adolescence (Casey, Giedd, & Thomas, 2000; Cycowicz, 2000; Goldman-Rakic, 1987).

Digit span tests require the participant to repeat the series in its given order; basically, this is serial position processing. Thus, besides the digit storage/recall processing, digit span tests require serial position processing. This type of processing is related to temporal processing and ordering, all of which are functions of the frontal lobes (McAndrews & Milner, 1991; Milner, Corsi, & Leonard, 1991; Shimamura, Janowsky, & Squire, 1990). Fuster (1995, 2000) in particular suggested that the prefrontal lobes, specifically the dorsolateral prefrontal cortex (DLPFC), mediate the formulation of temporal organizational structures that are necessary to learning and memory. Eslinger and Grattan (1994) showed that the serial position effect is altered in patients with DLPFC lesion. Serial position processing inherently involves proactive interference (PI). In this line, May, Hasher, and Kane (1999) found that digit span is critically influenced with PI manipulations. The orbitofrontal region of the frontal lobes is closely involved with susceptibility to interference, and this is another reason for altered serial processing (Eslinger & Grattan, 1994). These studies show that the frontal lobes that develop with adolescence are closely related to the digit span performance.

Methodological Considerations

As early as 1938, Blankenship had pointed out that in spite of the 146 studies in the literature, there is little “real” knowledge in the field of memory span. According to the author, this is because of the sample characteristics that varied with each study, the widely diverse methods of administering the test, the different methods of scoring, and the many kinds of materials used. The situation has not changed much since then; Henry and Millar (1991) pointed out that span size is influenced by method-specific factors. Thus, although the maximum mean digit span score that was observed in 15 studies was approximately 7, the data showed a variation of approximately 5 points at different ages (Dempster, 1981). Extreme variability in digit span had also been noted by Griffin and Heffernan (1983).

This study on aging employed a research approach that was controlled for the stated methodological factors. One control variable in the study was the level of education. This study obtained a significant effect of education on measures of digit span. In fact, the strength of association between education and the combined measures of digit span in MANOVA was even stronger than that for age. These findings showed that education is an important source of variability in digit span, and it should be used as a factor in the research design of all studies where the aim is the assessment of digit span.

Another factor that had been controlled in this aging study was the usage of organizational or mnemonic strategies. According to Ornstein, Naus, and Stone (1977), spontaneous usage of rehearsal techniques vary according to the developmental level. This effect is of such significance that the increase in children's digit span has been ascribed to the increasingly effective usage of mnemonic strategies (Burtis, 1982; Case, Kurland, & Goldberg, 1982; Chi, 1976; Dempster, 1978). However, with aging, both the quantity and the quality of rehearsal changes; rehearsal becomes less frequent and changes from an active one, involving usage of organizational strategies, to the less efficient passive rehearsal, involving item repetition that results in deteriorated memory performance (Jackson & Schneider, 1982).

Both the A–O score of the VADS–R Test and the D–F score of the WMS–R is obtained on aural presentation and through oral responding. The only difference between these scores is usage of organizational or mnemonic strategies; in WMS–R, the usage was ad lib, whereas in VADS–R Test such usage was prevented. Following the findings on the inadvertent usage of inefficient mnemonic or organizational strategies (Jackson & Schneider, 1982), the rate of decrease of the strategy-induced digit span as represented in D–F score was found to be faster in this study than the strategy-independent digit span represented in A–O score. Further, the difference between the D–F scores of participants with 5 to 8 years and more than 12 years of schooling was less marked than the difference between the A–O scores of the two types of graduates. Thus, the usage of strategies, as represented in the D–F scores, brought the digit span of the two education groups closer. Overall, these findings showed that the digit span that was obtained under ad lib usage of strategies did not represent the span that is obtained without the usage of strategies. Thus, the assumption that that digit span tests minimize rehearsal processes because participants repeat the remembered information immediately following presentation seems to be unwarranted (Esposito & Postle, 1999).

It follows that another source of variability in the digit span data may be the usage of mnemonic or organizational strategies, and if necessary controls are not provided, such factors act as contaminating variables. In a study on digit spans of the students of psychology and medicine, no difference was found between the VADS–R scores of the two groups of students when no strategy was used (Menli, Tavat, & Karakaş, 1993). However, when participants were instructed to use mnemonic strategies, students of medicine, whose education partially depends on the effective usage of such strategies, showed enhanced digit span. However, the instruction to use strategies did not affect the digit span of psychology students, whose training does not particularly require their usage. Thus, usage of strategies enhances digit span, but there are differences with respect to the efficiency by which these strategies are used.

With the adequately revised neuropsychological VADS–R Test and with adequate methodological controls, the distribution of the four basic digit span scores was approximated by the gamma distribution. Thus, the distribution was slightly negatively skewed. Although the range of the basic scores was 2 to 9, both the most frequently occurring score and the score that divided the population into two halves was 5.0 (except for a mode of 4.0 in the V–W score). The means varied between 4.77 and 5.16. However, only 1 participant in the total sample of 1,183 individuals obtained the highest score of 9 in all subtests.

The above statistics are in line with the maximum attainable score that Miller (1956) described as the "magical number 7, plus or minus 2." The digit span data of this study may be accepted as normative data on the strategy-independent digit span of the limited-capacity system of individuals from puberty to very old age

CONCLUSIONS

According to Koppitz (1977), the VADS Test measured STM, sequencing and sensory–motor integration. The digit span subtest of the WMS–R that required the participant to repeat the series in the forward direction (D–F) was identical, except for the strategy-inducing conditions of administration, to one subtest of the VADS–R Test, the A–O subtest. A group of authors identified the digit span tests as in the WMS–R with memory (Harmon, Clausen, & Scott, 1993; Lezak, 1995). However, according to a body of literature, the D–F score of the WMS–R represents not memory but attention–concentration (Dye, 1982; Roth, Conboy, Reeder, & Boll, 1990; Wechsler, 1987). In one study, it was found that the VADS–R and the D–F score of WMS–R were distributed under the same factors (Karakaş et al., 1996). The various memory scores of WMS–R were, however, distributed under four other factors. A second study (Genç-Açıkgöz, 1995) used the VADS–R, Logical Memory score, the D–F score of the WMS–R, and two tests of learning. One of these tests, the SDLT used digits and the other, AVLT, used words. The VADS–R and the D–F scores again loaded on the attention-concentration factor. Meanwhile, the other scores loaded on two other factors that were labeled as learning and memory.

These findings show that VADS–R Test is related to attention-concentration operation of information processing rather than to learning or memory. However, the literature on whether digit span performance is related to attention or memory or both is still not conclusive (Rosen & Engle, 1997). This mainly seems to be because the literature on the independence of these processes is largely not clear. According to Verghese and Pelli (1992), the restrictor is on the flow of information; the bottleneck thus occurs before the Millerian categorization bottleneck. Span thus applies to attention, and this is demonstrated in the usage of the concept, "span of attention." However, Miller (1956) defined the magical number 7 for both the span of attention and for immediate memory next to absolute judgement. In this vein, Cowan et al. (1999) defined the memory limit as the amount that can be subsumed in the focus of attention at one time. According to Fuster (2000), there are two short-term cognitive functions: perceptual memory and motor memory. However, the latter functions as an attentive set that anticipates action and prime the motor apparatus for it; thus the term *motor attention*. Vanderploeg, Schinka, and Retslaff (1994) showed the close relationship between the attentional and the mental tracking aspect of executive abilities (including digit span) and memory. In the face of these data, future research should be focused on the analysis of the basic cognitive processes that take place in digit span performance. One approach for a detailed functional analysis of digit span may be the study of patients with attention deficit hyperactivity disorder, who basically represent the extreme case for the cognitive function, attention-concentration, that digit span may be related to.

This study demonstrated the effect of education on the scores of the VADS–R Test in a broad range of ages between 13 and 98 years. It might be argued that over such a broad range of years, the educational system may have changed; for example, 5 to 8 years of schooling an older participant had might not be functionally equivalent to the 5 to 8 years of schooling a young adult had. However, this is a handicap of cross-sectional research for which there is no known methodological remedy. The alternative would be to use a longitudinal design that traces each individual from 13 years of age throughout the life span and to use control groups for each age level.

In this study, level of education was divided into different categories. It should be the task of future research to make a detailed investigation of the demonstrated effect of education. A major mission in such research should be to control for the effect of intelligence, either by way of research design or by way of the usage of statistical techniques. Such research would demonstrate whether education exerts a main effect or is just a "proxy" variable for intelligence. Another approach to be taken in prospective research may be to take education as a continuous variable and to define the participants educational status as actual years of schooling. An interesting line of research on the effect of education would be to have a control group of participants who would be at the same ages as the experimental group but who would not be attending junior or senior high school.

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