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Processing efficiency in preschoolers' memory span: Individual differences related to age and anxiety

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ABSTRACT

In self-paced auditory memory span tasks, the microanalysis of response timing measures represents a developmentally sensitive measure, providing insights into the development of distinct processing rates during recall performance. The current study first examined the effects of age and trait anxiety on span accuracy (effectiveness) and response timing (efficiency) measures from word and digit span performance in a preschool sample ($N = 76$, mean age = 57 months, $SD = 11$). Children were reassessed 8 months later using the same two tasks plus a test of nonword memory span and a measure of articulation rate. The results at the second time point (T2) confirmed the effects of age on both processing effectiveness and efficiency. Trait anxiety was an additional negative predictor of span effectiveness (especially for digit span) and efficiency (in the case of word and nonword span). The findings are discussed in the context of factors contributing to early short-term memory development and attentional control theory.

Introduction

Short-term memory (STM) represents the ability to generate and store mental tokens that code for entities in the environment (Feigenson, 2007). Its development has been studied extensively with a recent focus on its emergence during infancy and early childhood (Oakes & Bauer, 2007). The memory span procedure measures how many items a person can repeat back in sequence and has been widely used in adult and developmental studies as an important tool for investigating STM development. This procedure has a number of important advantages. First, it is simple enough to be understood by children as young as 2 years 10 months (Gathercole & Adams, 1993). Second, it is a developmentally

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sensitive index considering that it increases steadily between 3 and 10 years of age (Alloway, Gathercole, & Pickering, 2006; Dempster, 1985; Gathercole & Adams, 1993). Finally, research into the mechanisms involved in performing this task is ecologically relevant and has been related to comprehension and problem-solving abilities (Dempster, 1985), academic achievement (Alloway et al., 2005; Swanson, 1994), and general intelligence (Hutton & Towse, 2001).

A promising line of research investigating the development of auditory memory span was proposed by Cowan and colleagues (Cowan et al., 1992; Cowan et al., 1994; Cowan et al., 1998; Cowan et al., 2003; Cowan et al., 2006; Cowan, Saults, Nugent, & Elliott, 1999; Hulme, Newton, Cowan, Stuart, & Brown, 1999). By focusing on the self-paced nature of the verbal output, this research revealed the distinct informative value of different *response timing measures,* such as preparatory intervals, interword pauses, and word durations, in explaining the development of memory span performance. This provided an alternative account to the hypothesis that *articulation rate,* as an index of subvocal rehearsal, offers the best estimate of memory span. Developmental and adult evidence for a linear relation between articulation rate and verbal span has supported the latter hypothesis (e.g., Baddeley, Thomson, & Buchanan, 1975; Cowan et al., 1992; Gathercole & Adams, 1993; Henry, 1994; Hitch & Halliday, 1983), although the relation was not always straightforward (Hitch, Halliday, & Littler, 1993; Hulme & Muir, 1985). In addition, in the developmental context, measures of articulation rate have been shown to be themselves "contaminated" by memory effects and largely redundant with age in explaining variance in memory span (Ferguson, Bowey, & Tilley, 2002).

The microanalysis of response timing patterns also refined the more general account based on a global development in processing speed (Cerella & Hale, 1994; Kail, 1992; Kail & Salthouse, 1994; Salthouse, 1996). The global processing speed account, revised by Kail (1997), was recently challenged by the results of Ferguson and Bowey (2005), whose findings suggested that instead of being directly connected to memory span, "processing speed largely mediates developmental increases in some underlying construct that, in turn, influences memory span" (p. 108). However, the underlying mechanisms behind this mediation remain unclear.

Cowan and colleagues made several inferences regarding the underlying mechanisms of STM functioning from the microanalysis of response timing measures during overt recall. These indexes were analyzed concurrently with an articulation rate measure in both STM tasks (e.g., Cowan et al., 1994; Cowan et al., 1998; Hulme et al., 1999) and working memory (WM) tasks (Cowan et al., 2003). Several findings emerged as a result of these studies, which examined the interrelationships among age, response timing, and memory span. First, the speed of distinct output elements (especially interword pauses and preparatory intervals) represented reliable independent predictors of memory span performance. Second, interword pauses were affected by list length but unaffected by word length (Cowan et al., 1994). Third, in adults, interword pauses were much longer for nonwords than for words (Hulme et al., 1999). Fourth, interword pauses, preparatory intervals, and word durations were sensitive to individual differences in age and memory performance, so that (a) with age, and for a particular list length, all of these indexes decreased, suggesting more efficient processing; (b) speeded-speaking measures predicted span in first graders but not in older children, whereas interword pause durations predicted span in older children but not in younger children; and (c) word durations and interword pauses were shorter within children of a particular age who had higher memory spans (Cowan, 1992; Cowan et al., 1998). Therefore, response timing measures (beyond pure speeded-speaking estimates such as word durations) were shown to be sensitive to individual differences in age and memory performance. Because they were also influenced by the memory demands of the task, they represent an ideal candidate for the investigation of memory span development.

The current study investigated the mechanisms involved in the development of auditory memory span in preschoolers advocating the relevance of response timing measures in the analysis of STM processes. This age group is underresearched given that it might yield important insights into the emergence and early functioning of serial recall processes in children. There is evidence to show that the preschool years represent a time of intensive development in memory strategies, characterized by large individual variations in memory strategy (Schneider, Kron, Hűnnerkopf, & Krajewski, 2004; Sodian & Schneider, 1999). However, to our knowledge, no study so far has investigated the development of response timing patterns and their relation to memory span in preschoolers within a longitudinal framework.

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Individual variations in distinct response timing segments in this age group could be affected by trait anxiety. The most influential explanatory model regarding the anxiety–WM relationship is the processing efficiency theory (PET) (Eysenck & Calvo, 1992) or, in its revised form, the attentional control theory (ACT) (Derakshan & Eysenck, in press; Eysenck, Derakshan, Santos, & Calvo, 2007). At the core of the PET was the distinction between processing *effectiveness* (quality of task performance indexed by standard behavioral measures, i.e., accuracy) and processing *efficiency* (time taken to complete the task, subjective mental effort). The theory predicted that in high-anxious individuals, efficiency decreased as more effort and resources were invested to complete a task or to attain a given performance level because of concurrent resources being consumed by anxious thoughts (worries). Within the classical WM model and its subsequent revisions (Baddeley, 1986; Baddeley, 2000; Baddeley, 2007), the detrimental effects of anxiety were predicted to appear more at the level of the central executive, impairing attentional control, and of the phonological loop (Eysenck et al., 2007). The adverse effects of anxiety on performance efficiency become greater as overall task demands on the central executive increase (Eysenck et al., 2007). Research with adults has shown that high- and low-anxious individuals have comparable performance effectiveness but differ in terms of performance efficiency (Ansari, Derakshan, & Richards, 2008; Derakshan, Ansari, Hansard, Shoker, & Eysenck, in press; Derakshan & Eysenck, 1998; Ikeda, Iwanaga, & Seiwa, 1996; Markham & Darke, 1991).

Few studies have investigated the anxiety–memory relationship during early development, and there is no conclusive evidence concerning trait anxiety and its impact on processing efficiency on verbal STM span tasks in children (see Visu-Petra, Ciairano, & Miclea, 2006, for a review). With regard to this developmental context, Daleiden (1998) advocated that global approaches, emphasizing only anxiety-related attentional biases during the encoding stage, have been inconclusive in explaining anxiety effects on general memory performance. Such global approaches imply the presence of deficits in the initial attentional processes that interfere with the representation of the information in memory (Derryberry & Reed, 1996). Indeed, while solving a cognitive task, children with high anxiety were shown to produce significantly more task-inhibiting thoughts and ongoing negative evaluations than were those with low anxiety (Francis, 1988). Other studies describe difficulties in shifting of attention from internal to external stimuli (Kendall & Chansky, 1991).

Taking into account both effectiveness and efficiency indexes of memory performance, one study by Hadwin, Brogan, and Stevenson (2005) attempted to directly investigate the relationship between state anxiety and STM and WM in older children (9–10 years) within the explanatory framework of the PET. State anxiety (measured with the State–Trait Anxiety Inventory for Children [Spielberger, 1973], a self-report measure for children between 9 and 12 years of age) did not influence performance accuracy on the verbal memory task. However, it had a significant impact on the total time taken to complete the verbal memory tests and on self-reports of mental effort, both measures of distinct facets of processing efficiency.

The general aim of the current investigation was to replicate and extend the previously mentioned findings in several directions to improve our understanding of STM development during the preschool years. The main extensions consisted in the longitudinal nature of the study, the range of measures involved, and the relation to individual differences in trait anxiety. First, considering the *developmental trends* issue, a previous detailed analysis of response timing patterns in very young children has been performed for only a relatively small ($n = 16$) group of children, with a mean age of 4 years 5 months (Cowan et al., 1994), assessed at a single time point. Other previous studies with children have either compared preschoolers with much older children (4 years 5 months vs. 8 years 8 months [Cowan et al., 1994]) or compared school-aged children from different grades (first, third and fifth grades [Cowan et al., 1998, Experiment 1]). In the current longitudinal study, at the first time point (T1), the younger participant group ($n = 39$) represented a broader age range from 37 to 59 months with a mean age of 4 years ($SD = 8$ months); they were cross-sectionally contrasted with an older age group ($n = 37$, age range from 60 to 74 months, mean age 5 years 6 months [$SD = 4$ months]). Both age groups were reassessed 8 months later. This approach could reveal smooth developmental transitions that would gradually approximate the pattern seen in older children. However, it is equally possible that a different pattern of response timing might appear in preschoolers' verbal output measures, revealing that particular memory spans are accompanied by different profiles of processing rates in children of different ages (Cowan, 1999).

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A second extension of previous research was related to the *measures* included in this study. At the first time point, to investigate whether the response timing patterns were similar irrespective of stimulus type (Gathercole & Adams, 1993), we used both digit and word span measures. At this initial stage, parental reports of the children's anxiety levels were also taken using the Spence Preschool Anxiety Scale (Spence, Rapee, McDonald, & Ingram, 2001). At the second time point (T2), additional measures of nonword recall and articulation rate were introduced. Although the articulation rate measure has been widely used in relation to the response timing measures, there were three main reasons for including the nonword memory span task. First, Gathercole and Adams (1993) showed that it could be used with children as young as 2 years 10 months. Moreover, in the same study, nonword memory span was significantly associated with articulation rate, unlike digit span, probably because the former was more constrained by children's speech production skills than was the latter. Second, nonword memory span is considered as a particularly useful measure of children's STM abilities (Gathercole & Baddeley, 1989) because it provides a "purer" measure of phonological capacity without the confounds from long-term memory generated by the stimuli used in word or digit span tasks. Third, adult findings of within-participant relationships between measures of memory span and response timing vary according to the lexical status of items to be remembered, with shorter interword pauses for words than for nonwords (Hulme et al. 1999).

Extending the predictions of the ACT (Eysenck et al., 2007) to this age range, we decided to use the microanalysis of response timing measures to compare performance effectiveness and efficiency at different levels of trait anxiety. State anxiety could not be reliably assessed via self-reports at this young age, so parental ratings of child anxiety were used as a measure of trait anxiety (Spence et al., 2001). PET advocates that even when low- and high-anxious individuals have comparable performance effectiveness, group differences in efficiency can be inferred from differences in response time (Eysenck, Derakshan, Santos, and Calvo, 2007). We considered that a global measure of total response time (not differentiated across verbal output elements or across list lengths) used by Hadwin and colleagues (2005) might obscure the impact of anxiety on the specific processing that occurs during distinct response segments. Therefore, a final main aim of this study was to identify the concurrent and predictive effects of preschool anxiety on both performance effectiveness and efficiency indexes measured from the three types of span measures (digit, word, and nonword span).

Considering these objectives, we formulated the following predictions regarding, first, the effects of age and task demands and, second, the underresearched effects of trait anxiety on memory performance. First, we predicted that (a) the duration of all response timing indexes would decrease with age (from both cross-sectional and longitudinal perspectives) and increase with list length; (b) the durations of preparatory intervals and of interword pauses (but not of the words themselves) would represent independent predictors of span performance on the word, digit, and nonword span measures; and (c) conversely, span performance itself would represent a determinant of response timing measures. Second, our predictions regarding trait anxiety were that (a) trait anxiety level will not represent an independent predictor of span accuracy, but (b) the predictive negative effect of anxiety levels will be visible when the "strategic" processing efficiency elements, such as interword pauses and preparatory intervals, are considered, as compared with word durations.

Method

Participants and procedure

Our initial sample at T1 consisted of 116 preschoolers recruited from kindergartens in the northwest of Romania. However, 36 children (mean age = 71.13 months, *SD* = 7.31) could not be followed up at T2 because they were already in school. In the current sample, including the preschoolers evaluated at both T1 and T2, there was a relatively low dropout rate, with 2 children no longer being at the same kindergarten at T2 (60 and 63 months of age at T1) and 2 children failing to cooperate with the experimenter during one of the two phases of the study (43 and 54 months of age at T1). Therefore, data from 76 preschoolers (46 boys and 30 girls) were included in the current report.

At T1, the children had an age range between 37 and 74 months (mean age = 57 months, *SD* = 11). Consistent with our aim to investigate the effect of age on the development of STM processes, the participants from T1 were divided into two age groups: Age Group 1, consisting of 39 children between 3 and 5 years at T1, and Age Group 2, consisting of 37 children between 5 years and 6 years 2 months at T1 (see Table 1 for demographic data at T1 and T2).

At T1, each child was individually tested in a quiet area of the kindergarten for a single session lasting up to 15 to 20 min. The tests were administered in a fixed sequence designed to alternate task demands (verbal and nonverbal) and to reduce fatigue and boredom. At T2 8 months later, only one visual–spatial measure and the verbal STM tasks were administered (digit span, word span, and the new measure of nonword span) along with the measure of articulation rate; again, the order of administering the tasks was fixed.

Measures

Spence Preschool Anxiety Scale

At T1, we used the Spence Preschool Anxiety Scale (Spence et al., 2001) to assess individual differences in trait anxiety. This instrument represents a widely used measure of trait anxiety in preschoolers adapted from the Spence Children's Anxiety Scale (SCAS) (Spence, 1997) to suit younger children and assessed via parental report. The scale consists of 28 anxiety items, 5 posttraumatic stress disorder items (nonscored), and 1 open-ended nonscored item. It provides an overall measure of anxiety together with scores on five subscales, each tapping a specific aspect of child anxiety. Each parent rated, on a 5-point scale, the concordance between the child's behavior and that described by the questionnaire items. The total score for an individual child was entered as the measure of his or her trait anxiety level. The Romanian version of the test has good internal consistency (Cronbach's alpha = .87 for mother reports and Cronbach's alpha = .89 for father reports [Ţincaş, Dragoş, Ionescu, & Benga, 2007]) and moderate test–retest reliability ($r = .59$).

Due to the lack of parental reports for all children at T2 (only 76% returned the questionnaires), only the anxiety data from T1 are analyzed. The total anxiety score in our sample (Age Group 1: $M = 27.23$, $SD = 14.31$; Age Group 2: $M = 26.21$, $SD = 13.30$) with a nonsignificant age effect, $F(1, 75) < 1$, was slightly lower but very similar to the Romanian standardization sample's score for the same age band of 3 to 6 years ($M = 30.46$, $SD = 14.92$).

Digit span

The digit span procedure was derived from the standardized administration of the digits forward subtest of the digit span test, as described in the Wechsler Intelligence Scale for Children–Third Edition (WISC-III) manual (Wechsler, 1991). The procedure for digit span was identical to the one used for word span and nonword span. Memory performance was assessed by the experimenter reading aloud series of digits/words/nonwords at the rate of one item per second, and the child was instructed to repeat them back immediately in the correct sequence without any discrete recall cue. Three trials

Table 1
Demographic data and aggregate span measures at T1 and T2

Variable	T1		T2	
	Age Group 1 (*n* = 39)	Age Group 2 (*n* = 37)	Age Group 1 (*n* = 39)	Age Group 2 (*n* = 37)
Age range (months)				
Minimum	37	60	46	68
Maximum	59	74	67	83
Mean age (*SD*)/Age group	48.43 (7.83)	66.10 (4.41)	56.79 (6.07)	74.08 (5.11)
Mean age (*SD*)/Time	57.04 (10.93)		64.98 (10.46)	
Aggregate word span (*SD*)	3.41 (0.74)	3.89 (0.64)	3.84 (0.58)	4.31 (0.64)
Aggregate digit span (*SD*)	3.87 (0.84)	4.32 (0.80)	4.04 (0.83)	4.45 (0.78)
Aggregate nonword span (*SD*)	—	—	3.10 (0.42)	3.13 (0.44)

Note. Standard deviations are in parentheses.

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were given at each list length, beginning with a list length of 2 items. If recall was correct on two or more of the three trials for each list length, the sequence length was increased by 1 item. In each span task, the change in the number of elements was signaled by the experimenter telling the child, "Now let's try it with *n* [words/numbers/made-up words]" (a cue that potentially warned the child about the list length and signaled the end of a presented sequence of items). If the child failed more than one list in a list length, testing was discontinued.

Word span

A list of nine common two-syllable words was chosen to provide a test of word repetition directly comparable to the other span measures (Romanian words *minge, masă, birou, vacă, mână, creion, bancă, stradă,* and *apă*, meaning *ball, table, desk, cow, hand, pencil, bench, street,* and *water,* respectively). In a preliminary study investigating the age of acquisition of Romanian words (Dobrean, 2008), it was shown that by 36 months of age (the youngest child in the current investigation was 37 months), more than 90% of the children were already using six of the words from the current investigation (*minge, masă, vacă, mână, creion,* and *apă*) and more than 70% were using the other three words (*birou, bancă,* and *stradă*). The selection of a constant number of syllables (two) was made to avoid the word length effect (not analyzed in the current study) and to provide a more directly comparable measure to the word length of items from digit span (in Romanian, five of nine digits have two syllables). The testing procedure corresponds to the one used for the digit span task.

Nonword span

This measure was introduced only at T2 of the evaluation. As a pilot study on 5 children showed, using two-syllable nonwords (providing a closer match to the stimuli in the word and digit span) produced significantly more phonological errors on list lengths of 2 and 3 (LL2 and LL3, respectively) than did one-syllable nonwords. Taking into account that for the analysis of response timing measures we would use only correctly repeated sequences, we decided to rely on one-syllable nonwords as the experimental stimuli for this task. A set of nine one-syllable nonwords was selected from the Romanian adaptation of the nonword repetition subtest of the Automated Working Memory Assessment battery (Alloway, 2007), low in phonological complexity and with medium or low "wordlikeness," as evaluated by three independent adult raters (see Gathercole, Hitch, Service, & Martin, 1997, for a discussion on the adequacy of using adult ratings of wordlikeness to select experimental stimuli for children). The administration procedure was similar for both digit and word span. Each child was told that he or she would hear made-up words and should try to repeat them. Although the responses were audiotaped, the experimenter judged during test administration whether the child produced a sound that differed phonemically from the target nonword, which was considered as an error (except for stable misarticulations). Similar to the other span tasks, if the child had more than one erroneous list repetition in a list length, testing was discontinued.

Articulation rate

This measure was also used only at T2. Each child was asked to repeat, as quickly as possible, the words *leu* and *nas* (meaning *lion* and *nose*). After one correct repetition of the pair, the child was asked to repeat the pair twice and then five times (until the experimenter would say "stop" so as to prevent concurrent counting of repetition times from the child). We chose one-syllable words for the pair that needed to be repeated considering the documented memory "contamination" of more complex speeded-speaking sequences (Ferguson et al., 2002).

The time taken to produce the five repetitions was calculated from the audiotape recording, and this total time was then converted to the mean number of words per second. For children who failed to produce five repetitions (3 children repeated the pair four times and 2 children repeated the pair only three times), the articulation rate was calculated as the mean words per second from the available number of repetitions. The mean articulation rate for the whole sample was 2.28 words/s, *SD* = 0.62 (see Table 2 for data regarding each age group).

Table 2
Response timing measures across list lengths as a function of age group and time

Measure	T1		T2	
	Age Group 1	Age Group 2	Age Group 1	Age Group 2
Word span (s)				
Preparatory interval LL2	.56 (.11)	.49 (14)	.52 (.13)	.48 (.10)
Preparatory interval LL3	.81 (.18)	.69 (.16)	.73 (.14)	.63 (.11)
Word duration LL2	.48 (.07)	.43 (.07)	.46 (.05)	.45 (.07)
Word duration LL3	.49 (.06)	.45 (.06)	.46 (.04)	.45 (.06)
Interword pause LL2	.10 (.06)	.13 (.05)	.10 (.07)	.08 (.03)
Interword pause LL3	.15 (.06)	.20 (.10)	.14 (.07)	.10 (.04)
Digit span (s)				
Preparatory intervalLL2	.46 (.13)	.38 (.10)	.34 (.09)	.29 (.09)
Preparatory interval LL3	.56 (.16)	.48 (.10)	.48 (.12)	.44 (.14)
Word duration LL2	.44 (.08)	.38 (.07)	.41 (.06)	.39 (.05)
Word duration LL3	.42 (.07)	.40 (.06)	.42 (.06)	.40 (.06)
Interword pause LL2	.19 (.08)	.18 (.05)	.14 (.03)	.12 (.03)
Interword pause LL3	.22 (.06)	.24 (.04)	.14 (.04)	.13 (.03)
Nonword span (s)				
Preparatory interval LL2	–	–	.58 (.17)	.53 (.16)
Preparatory interval LL3			.76 (.21)	.71 (.19)
Word duration LL2			.46 (.07)	.47 (.05)
Word duration LL3			.50 (.08)	.50 (.08)
Interword pause LL2			.20 (.07)	.20 (.04)
Interword pause LL3			.26 (.07)	.23 (.09)
Articulation rate (words/s)	–	–	2.16 (0.63)	2.41 (0.58)

Note. Standard deviations are in parentheses. LL, list length.

Types of analyses

Span measures

A detailed measure, termed aggregate span, was calculated to reflect performance effectiveness across lists following the procedure presented by Cowan and collaborators. After determining a base span as the highest list length at which all three trials were passed correctly, a score of 0.33 was added to this base span for every list of a longer length that was correctly recalled. For example, if a child correctly recalled three two-word lists, two three-word lists, and one four-word list, an aggregate span of 2 + 0.66 + 0.33 = 3 would be awarded (for more details on the scoring procedure, see Cowan et al., 2003).

Response timing measures

The whole interaction was recorded on audiotape and analyzed using a speech waveform editor (CoolEditPro, Version 2.0) on a portable computer. The oscillographic display characterizing each response timing measure (preparatory interval, interword pause, and word duration) was selected by two trained assistants who concomitantly listened to the selected segment through headphones. Response timing measurements were taken only for lists correctly recalled (all items recalled in the correct order) by both age groups at both T1 and T2. This reduced the response timing analysis to list lengths of 2 and 3 items (LL2 and LL3, respectively) because most of the children had complete data (for all three trials) for these list lengths (except 1 child lacking digit span–LL3 at T1, 2 children lacking word span–LL3 at T2, and 3 children lacking LL3 for nonword span [see the description bellow for more details]) but not for longer list lengths. Timing measurements were averaged across trials of a particular length for each child (similar to the procedure described in Cowan et al., 2003).

Two children (48 and 52 months of age at T2) did not complete any LL3 trials on word span at T2. One child (72 months of age) failed to repeat any of the LL3 items on the digit span at T1. The response timing data for the particular task on which the children lacked LL3 recall were not included in the analysis. In the case of nonword span, 3 children (48, 60, and 69 months of age) failed to repeat any LL3 list, and their results for this task were not included in the analysis. For each task, trials on which the response time was more than 3 standard deviations from the mean for that particular age group were excluded; this happened only in the case of three trials at LL3 on word span, which were eliminated from the final analysis (the average for the list length that had an outlier trial was calculated from the other two trials). The two raters analyzed the same recordings for 27 randomly selected children at T1; correlations between means on the response timing measures were calculated. The values were as follows: for the total response duration, $r = .98$; for preparatory intervals, $r = .93$; for interword pauses, $r = .87$; and for word duration, $r = .73$.

Results

Performance effectiveness

Descriptive statistics for the aggregate memory span measures for the whole sample are reported in Table 1. Separate analyses of variance (ANOVAs) of aggregate span were conducted with age group (1 vs. 2) as a between-participant factor and with time (T1 vs. T2) and task type (word vs. digit span) as within-participant factors. Results for nonword span are presented separately because this measure was taken only at T2.

Looking at memory performance on word and digit span, we found that children significantly increased their memory spans at T2 ($M = 4.16$, $SD = 0.75$) compared with T1 ($M = 3.87$, SD = 0.82), as revealed by the significant effect of time, $F(1, 74) = 38.83$, $p < .001$, $MSE = 6.24$, partial $\eta^2 = .34$. They had better scores on digit span ($M = 4.17$, $SD = 0.84$) than on word span ($M = 3.86$, $SD = 0.72$), as revealed by the main effect of task type, $F(1, 74) = 37.35$, $p < .001$, $MSE = 7.22$, partial $\eta^2 = .33$. There was also a significant effect of age group, $F(1, 74) = 8.87$, $p < .01$, $MSE = 15.42$, partial $\eta^2 = .11$, with older children having higher spans across tasks at both times of evaluation ($M = 4.25$, $SD = 0.75$) than younger children ($M = 3.80$, $SD = 0.79$). We found that there was a significant interaction between time and task type, $F(1, 74) = 12.79$, $p < .01$, $MSE = 1.36$, partial $\eta^2 = .15$. Children increased their word spans more than digit spans from T1 (word span: $M = 3.66$, $SD = 0.73$; digit span: $M = 4.09$, $SD = 0.85$) to T2 (word span: $M = 4.07$, $SD = 0.66$; digit span: $M = 4.24$, $SD = 0.83$).

On nonword span at T2, children had significantly lower aggregate spans ($M = 3.12$, $SD = 0.43$) than on word span ($M = 4.09$, $SD = 0.65$), $F(1, 75) = 200.06$, $p < .001$, $MSE = 37.99$, partial $\eta^2 = .73$, and on digit span ($M = 4.25$, $SD = 0.83$), $F(1, 75) = 175.94$, $p < .001$, $MSE = 52.49$, partial $\eta^2 = .70$, both measured at T2. Belonging to an age group did not significantly influence the accuracy of performance on this task, $F(1, 73) < 1$.

Performance efficiency

The means and standard deviations for the response timing indexes, averaged across serial positions for each list length and each age group at T1 and T2, are presented in Table 2. Repeated measures ANOVAs were conducted for each response timing index (preparatory intervals, word durations, and interword pauses) from word and digit span with time (T1 vs. T2) and list length (LL2 vs. LL3) as within-participant factors and with age group (1 vs. 2) as a between-participant factor. For nonword span, only the effects of age group and list length were calculated.

On word span, preparatory intervals were significantly shorter in Age Group 2 ($M = .57$, $SD = .11$) when compared with Age Group 1 ($M = .65$, $SD = .12$) and at T2 when compared with T1 (T2: $M = .59$, $SD = .11$; T1: $M = .63$, $SD = .13$); this index increased significantly for LL3 when compared with LL2 (LL3: $M = .71$, $SD = .16$; LL2: $M = .51$, $SD = .12$). Analyses confirmed these observations with a significant main effect of age group, $F(1, 72) = 15.75$, $p < .001$, $MSE = .03$, partial $\eta^2 = .18$, a significant effect of time, $F(1, 72) = 7.28$, $p < .01$, $MSE = .02$, partial $\eta^2 = .09$, and a highly significant effect of list length, $F(1, 72) = 203.16$, $p < .001$, $MSE = .02$, partial $\eta^2 = .74$. There was a significant interaction between time and list length, $F(1, 72) = 5.12$, $p < .05$, $MSE = .009$, partial $\eta^2 = .07$, suggesting that at T2 children's preparatory intervals decreased from LL3 (T1: $M = .75$, $SD = .18$; T2: $M = .68$, $SD = .14$) more than those from LL2 (T1: $M = .52$, $SD = .13$; T2: $M = .50$, $SD = .12$). No other interaction effect proved to be significant.

On digit span, the pattern of preparatory intervals was very similar. There was a significant main effect of age group, $F(1, 73) = 8.79$, $p < .01$, $MSE = .03$, partial $\eta^2 = .10$. [Children from Age Group 2 ($M = .40$, $SD = .10$) had shorter preparatory intervals than those from Age Group 1 ($M = .46$, $SD = .13$)], of time, $F(1, 73) = 33.86$, $p < .001$, $MSE = .02$, partial $\eta^2 = .32$, (T1: $M = .47$, $SD = .12$; T2: $M = .39$, $SD = .10$), and of list length, $F(1, 73) = 212.71$, $p < .001$, $MSE = .005$, partial $\eta^2 = .75$ (LL2: $M = .37$, $SD = .12$; LL3: $M = .49$, $SD = .14$). However, the interaction between time and list length, although again significant, $F(1, 73) = 7.29$, $p < .01$, $MSE = .005$, partial $\eta^2 = .09$, revealed that on this task time had a stronger effect on LL2 (T1: $M = .42$, $SD = .13$; T2: $M = .32$, $SD = .10$) than on LL3 (T1: $M = .52$, $SD = .14$; T2: $M = .46$, $SD = .13$) (see Table 2).

Word durations represent another important response timing measure. The same analyses were conducted to investigate the impact of age group, time, and list length on this variable. In the case of word span, only age group had a significant effect, $F(1, 72) = 8.70$, $p < .01$, $MSE = .006$, partial $\eta^2 = .11$, as children from Age Group 2 ($M = .44$, $SD = .05$) had shorter word durations than those from Age Group 1 ($M = .47$, $SD = .05$). In the case of digit span, there was again a significant main effect of age group, $F(1, 73) = 5.52$, $p < .05$, $MSE = .01$, partial $\eta^2 = .07$, with Age Group 1 having longer word durations ($M = .42$, $SD = .06$) than Age Group 2 ($M = .40$, $SD = .05$). In addition, there was a significant interaction between age group and list length, $F(1, 73) = 4.65$, $p < .05$, $MSE = .001$, partial $\eta^2 = .06$, suggesting that the effect of age group was stronger on LL2 (Age Group 1: $M = .42$, $SD = .01$; Age Group 2: $M = .39$, $SD = .06$) than on LL3 (Age Group 1: $M = .42$, $SD = .06$; Age Group 2: $M = .40$, $SD = .06$). No other main effects or interaction effects proved to be significant.

In the literature, interword pauses are considered the most relevant measure of covert memory search processes (Cowan, 1999). An interesting pattern of results emerged for both word and digit span. First, in the case of word span, children had shorter interword pauses at T2 ($M = .11$, $SD = .05$) than at T1 ($M = .15$, $SD = .06$) and on LL2 ($M = .10$, $SD = .06$) than on LL3 ($M = .16$, $SD = .08$). To support this idea, there was a significant main effect of time, $F(1, 72) = 21.87$, $p < .001$, $MSE = .004$, partial $\eta^2 = .23$, and of list length, $F(1, 72) = 33.18$, $p < .001$, $MSE = .004$, partial $\eta^2 = .32$. In addition, there was a significant interaction between time and age group, $F(1, 72) = 18.52$, $p < .001$, $MSE = .004$, partial $\eta^2 = .21$. Whereas at T1 older children had longer interword pauses (Age Group 2: $M = .16$, $SD = .06$) than younger children (Age Group 1: $M = .13$, $SD = .04$), at T2 this situation was reversed, with older children having shorter interword pauses ($M = .10$, $SD = .03$) than younger children ($M = .12$, $SD = .05$). Finally, there was also a significant interaction between time and list length, $F(1, 72) = 5.53$, $p < .05$, $MSE = .004$, partial $\eta^2 = .20$, revealing that the significant effect of time was exerted more on LL3 (T1: $M = .17$, $SD = .09$; T2, $M = .12$, $SD = .06$) than on LL2 (T1: $M = .12$, $SD = .05$; T2, $M = .09$, $SD = .06$).

Second, in the case of digit span, there was again a highly significant main effect of time, $F(1, 73) = 145.28$, $p < .001$, $MSE = .003$, partial $\eta^2 = .66$, and of list length, $F(1, 73) = 25.93$, $p < .01$, $MSE = .002$, partial $\eta^2 = .26$. More specific, children had shorter interword pauses at T2 ($M = .13$, $SD = .03$) than at T1 ($M = .21$, $SD = .05$) and on LL2 ($M = .16$, $SD = .06$) than on LL3 ($M = .18$, $SD = .07$). The interaction between time and list length was highly significant, $F(1, 73) = 29.36$, $p < .001$, $MSE = .001$, partial $\eta^2 = .29$. The effect of time was again much stronger on LL3 (T1: $M = .23$, $SD = .05$; T2: $M = .13$, $SD = .03$) than on LL2 (T1: $M = .19$, $SD = .07$; T2: $M = .13$, $SD = .03$). For digit span, the interaction between time and age group was only marginally significant, $F(1, 73) = 3.72$, $p = .058$, $MSE = .003$, partial $\eta^2 = .05$. T1 results indicated shorter interword pauses for Age Group 1 ($M = .20$, $SD = .06$) than for Age Group 2 ($M = .21$, $SD = .04$), whereas at T2 the situation was reversed, with younger children having longer interword pauses ($M = .14$, $SD = .03$) than older children ($M = .12$, $SD = .03$).

A supplementary analysis was conducted to reveal the true effects of age across time points. This analysis was motivated by the fact that Age Group 1 at T2 actually had a lower mean age than Age Group 2 at T1 (57 vs. 66 months). So, we compared all response timing indexes between these two groups, also considering the effect of list length. In general, the results confirmed the predicted developmental trends, that is, chronologically older children from Age Group 2 at T1 obtaining shorter response timing indexes. Only in the case of interword pauses did we find a reversed pattern, especially for LL3; on both word and digit span, older children (Age Group 2 at T1) had longer interword pauses (word span: $M = .20$, $SD = .10$; digit span: $M = .24$, $SD = .04$) than younger children (Age Group 1 at T2) (word span: $M = .14$, $SD = .07$; digit span: $M = .14$, $SD = .04$), $F(1, 74) = 9.11$, $p < .01$, $MSE = .008$, partial

η^2 = .11, and $F(1, 73)$ = 134.61, p < .001, MSE = .002, partial η^2 = .65, respectively. This could suggest either that there was some difference between the samples at T1 that justified this unexpected increase in interword pauses for older children or that children from Age Group 1 had shorter interword pauses at T2 because of practice effects, a factor from which older children at T1 had not benefited.

The results for response timing indexes are presented separately in the case of nonword span because of the exploratory nature of the findings and because we collected data only at T2. Thus, only the variables of age group and list length were entered in the ANOVAs. When analyzing the preparatory intervals, there was a significant main effect of list length, $F(1, 71)$ = 82.31, p < .001, MSE = .015, partial η^2 = .54, with much longer durations of these indexes for LL3 (M = .74, SD = .20) than for LL2 (M = .56, SD = .17). The effect of age group on this index was nonsignificant, $F(1, 71)$ = 1.20, *ns.* Looking at word durations, there was again a significant main effect of list length, $F(1, 71)$ = 22.19, p < .001, MSE = .003, partial η^2 = .24, with longer spoken durations for the words in LL3 (M = .50, SD = .08) than in LL2 (M = .46, SD = .06). There was no significant effect of age group or of the interaction between age group and list length. Finally, regarding the interword pauses, there was the same main effect of list length, $F(1, 71)$ = 22.54, p < .001, MSE = .004, partial η^2 = .24 (LL3: M = .25, SD = .08; LL2: M = .20, SD = .06).

The measure of articulation rate, used only at T2, showed a marginally significant effect of age group, $F(1, 76)$ = 3.05, p = .08, MSE = .37, partial η^2 = .04, with older children pronouncing more words per second than younger children (M = 2.41, SD = 0.58, vs. M = 2.16, SD = 0.63), although there was a large variance within both groups in their articulation rates.

Relations among performance effectiveness, efficiency, and anxiety

Correlations among measures

To obtain a preliminary indication of the associations between the measures of performance effectiveness (aggregate spans) and the measures of performance efficiency (response timing indexes and articulation rate), and to relate them to age and anxiety, we entered the principal measures into a correlation matrix (see Table 3). Composite indexes of each response timing measure were calculated by averaging the indexes from LL2 and LL3. We briefly discuss some relevant findings, considering that the extensive regression analyses will help to clarify the nature of these relationships.

It appears that for the age range covered by this study at T2 (mean age = 5 years 5 months), the pattern of the relation between articulation rate and memory span was already "mature"; children who spoke faster also had better memory spans in all three span tasks (word span: r = .31, p < .01; digit span: r = .27, p < .05; nonword span: r = .23, p < .05). As for the relation between distinct response timing measures at T2, there was a significant negative relation between articulation rate and preparatory intervals for all tasks (digit span: r = –.44, p < .01; word span: r = –.30, p < .01; nonword span: r = –.32, p < .01), and only in the case of digit span was there a negative relation with interword pauses (r = –.45, p < .01). This overall pattern of associations suggests that the children who spoke faster were also the ones who took less time to prepare their responses (for digit span, also the ones with shorter interword pauses) and the ones who had better memory spans (this hypothesis is further investigated in the regression analyses).

Individual anxiety scores, although negatively (and moderately) related to aggregate span scores at T2 (word span: r = –.25, p < .05; digit span: r = –.24, p < .05; nonword span: r = –.21, *ns*), were largely unrelated to the response timing measures except for a positive relation to preparatory intervals for word span and nonword span at T2 (r = .30, p < .01, and r = .26, p < .05, respectively). This suggests that the impact of anxiety on memory performance might not necessarily be reflected only in reaction times (at least not for LL2 and LL3). This hypothesis and other hypotheses are investigated in the following regression analyses.

Regression analyses

Two types of hypotheses were tested with the multiple regression analyses, identifying the best predictors of span accuracy (aggregate span) and of span efficiency (response timing indexes) for each of the three span tasks (word, digit, and nonword span).

First, to see whether different response timing measures and articulation rate brought independent contributions to variance in span scores, three hierarchical regression analyses were conducted (one

Table 3
Correlations among main measures: Age, Spence score, aggregate span, response timing measures, and articulation rate at T1 and T2 for word, digit, and nonword span

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Age	–	–.06	.38*	.46*	–.00	–.40*	–.39*	.37*	–.18	–.41*	–.38*	.06	–.31*	–.05	.34*
2. Spence score	–.06	–	–.15	–.25	–.21	.08	.17	–.03	.08	.30*	.17	.14	.26	.22	–.00
3. Aggregate span T1	.33*	–.12	—	.69*	.44*	–.15	–.34*	–.21	–.16	–.13	–.21	–.11	–.22	–.02	.28
4. Aggregate span T2	.33*	–.24	.84*	—	.39*	–.16	–.52*	–.15	–.28	–.28	–.29	–.04	–.27	–.16	.31*
5. Aggregate span nonword memory span	–.00	–.21	.28	.33*	—	–.09	–.17	–.18	–.16	.07	.10	–.27	–.04	–.22	.23
6. Word duration T1	–.39*	–.07	–.26	–.30*	.05	—	.08	–.24	.15	.25	.31*	.20	.18	–.06	–.23
7. Preparatory interval T1	–.43*	–.04	–.39*	–.39*	.00	.21	–	.04	.26	.44*	.11	.19	.28	.07	–.26
8. Interword pause T1	–.00	.08	–.10	–.18	.07	.40*	.26	—	.18	–.17	.00	.20	–.05	–.00	.01
9. Word duration T2	–.22	.06	–.11	–.13	–.15	.43*	.12	.18	—	.33*	.13	.35*	.33*	.13	–.28
10. Preparatory interval T2	–.39*	.08	–.20	–.27	–.07	.21	.44*	.23	.29	—	.23	.10	.53*	.16	–.30*
11. Interword pause T2	–.37*	.10	–.07	–.17	–.05	.22	.23	.02	.33*	.65*	—	.14	.27	.10	–.14
12. Nonword memory span duration	.06	.14	–.04	–.05	–.27	.22	.08	.22	.42*	.11	.23	—	.30	.25	–.16
13. Nonword memory span preparatory interval	–.31*	.26	–.22	–.27	–.04	.22	.32*	.19	.24	.54*	.42*	.30	—	.30	–.32*
14. Nonword memory span interword pause	–.05	.22	–.06	–.10	–.22	–.04	.07	.13	.10	.11	.09	.25	.30	—	.04
15. Articulation rate	.34*	–.00	.25	.27	.23	–.22	–.29	–.06	–.19	–.44*	–.45*	–.16	–.32*	.04	—

Note. The correlations above the diagonal are for word span, and those below the diagonal are for digit span. Considering the large number of comparisons, the significance level for the correlation coefficients was set to $p < .01$.

* $p < .01$.

for each type of span task). Aggregate span at T2 was in each case the dependent variable. Age and articulation rate (Step 1) and processing efficiency (the response timing indexes from T1 and T2) (Step 2) were subsequently entered into the analyses. Finally, anxiety scores were added as a potential predictor (Step 3) to see whether individual differences in anxiety levels would make unique contributions to span, above their influences on the speech timing variables. In the case of nonword span, only concurrent relations with the response timing measures could be measured because this task was introduced only at T2.

Table 4 summarizes the results of these regression analyses for all three tasks included in this study. In the investigated sample, using only age, articulation rate, response timing measures, and anxiety scores as predictors, we managed to account for significant portions of the variance in aggregate span scores: 47% for word span, 29% for digit span, and 20% for nonword span (but see Table 4 for adjusted R^2 values, taking into account the number of predictors included in the study). However, the contributions of different predictors to the aggregate span scores were not identical across distinct tasks. Age had a significant contribution in predicting aggregate word span, $\beta = .40$, $p < .01$, and digit span, $\beta = .27$, $p < .05$, but not nonword span, $\beta = -.10$, *ns*. Articulation rate had a significant independent contribution only for nonword span, $\beta = .27$, $p < .05$, remaining its best (and only) significant predictor even when introducing the efficiency and anxiety measures.

The response timing measures from T1 and T2 introduced at Step 2 brought an additional significant contribution of 20% for word span and 10% for nonword span but not for digit span. Preparatory intervals at T1 were the strongest predictors for word span performance, $\beta = -.35$, $p < .01$, and were marginally significant for digit span, $\beta = -.25$, $p < .06$, followed by interword pauses at T1 (word span: $\beta = -.25$, $p < .05$; nonword span: $\beta = -.22$, $p < .06$).

A final significant contribution was brought by the anxiety scores, which accounted for an additional significant 4 and 7% of the variance in word and digit span scores, respectively, above the effects of age, articulation rate, and response timing.

Second, we aimed to identify the best predictors of processing efficiency at the second time point. For each task, we conducted three multiple regressions: one for each relevant response timing index (preparatory intervals, word durations, and interword pauses). Following the same logic as processing effectiveness, the predictors age and articulation rate (Step 1), processing effectiveness from T1 and T2 (aggregate spans) (Step 2), and finally anxiety levels (Step 3) were entered. Table 5 represents the re-

Table 4
Regression analyses predicting aggregate spans at T2

Step/Variable	Outcome variables								
	AS–word span[a] (N = 74)			AS–digit span[b] (N = 75)			AS–nonword span[c] (N = 73)		
	B	SE B	β	B	SE B	β	B	SE B	β
Step 1									
Age	.03	.00	.40**	.02	.01	.27*	−.00	.01	−.10
Articulation rate	.18	.12	.17	.24	.16	.18	.18	.09	.27*
Step 2									
Age	.02	.00	.36**	.01	.01	.11	−.01	.01	−.05
Articulation rate	.08	.11	.08	.16	.17	.12	.19	.09	.27*
Preparatory interval T1	−1.7	.58	−.35**	−1.65	.88	−.25†			
Word duration T1	−.04	1.19	−.00	−2.14	1.70	−.17			
Interword pause T1	−2.93	1.30	−.25*	.44	2.18	−.03			
Preparatory interval T2	.30	.68	.05	−.51	1.34	−.06	.44	.35	.17
Word duration T2	−.75	1.35	−.06	.41	2.04	.03	−1.50	.84	−.21
Interword pause T2	−1.48	1.49	−.10	1.50	4.38	.05	−.88	.47	−.22†
Step 3									
Age	.02	.00	.39**	.01	.01	.07	−.01	.01	−.05
Articulation rate	.11	.11	.10	.17	.17	.12	.20	.09	.29*
Preparatory interval T1	−1.68	.57	−.33**	−1.88	.85	−.28*			
Word duration T1	−.00	1.16	−.00	−2.88	1.67	−.24			
Interword pause T1	−3.01	1.28	−.25*	.39	2.13	.02			
Preparatory interval T2	.65	.69	.11	−.50	1.29	−.06	.56	.35	.21
Word duration T2	−.78	1.31	−.06	.76	1.96	.05	−1.44	.83	−.21
Interword pause T2	−1.05	1.47	−.07	2.33	4.22	.08	−.78	.47	−.20
Spence score	−.01	.00	−.20*	−.02	.01	−.27*	−.01	.01	−.20

Note. AS, aggregate score.
[a] $R^2 = .24$ for Step 1 (adjusted $R^2 = .22$), $\Delta R^2 = .20$ for Step 2, *ps* < .01 ($R^2 = .44$, adjusted $R^2 = .37$), $\Delta R^2 = .04$ for Step 3, *ps* < .05 ($R^2 = .47$, adjusted $R^2 = .40$).
[b] $R^2 = .13$ for Step 1 (adjusted $R^2 = .11$), $\Delta R^2 = .09$ for Step 2, *ns* ($R^2 = .23$, adjusted $R^2 = .13$), $\Delta R^2 = .07$ for Step 3, *ps* < .05 ($R^2 = .29$, adjusted $R^2 = .20$).
[c] $R^2 = .06$ for Step 1 (adjusted $R^2 = .04$), $\Delta R^2 = .10$ for Step 2, *ps* < .05 ($R^2 = .17$, adjusted $R^2 = .10$), $\Delta R^2 = .04$ for Step 3, *ns* ($R^2 = .20$, adjusted $R^2 = .13$).
† $p < .06$.
* $p < .05$.
** $p < .01$.

sults for the “strategic” indexes from word and digit span (preparatory intervals and interword pauses), but we also mention significant findings in the prediction of word durations. Age significantly predicted preparatory intervals and interword pauses for word span, $\beta = -.36$, $p < .01$, and $\beta = -.38$, $p < .01$, respectively, and for digit span, $\beta = -.28$, $p < .05$, and $\beta = -.24$, $p < .05$, respectively, and was marginally significant for nonword span preparatory intervals, $\beta = -.23$, $p < .06$. The predictive effect of articulation rate was significant for preparatory intervals from word span and marginally significant for preparatory intervals from nonword span, $\beta = -.35$, $p < .01$, and $\beta = -.24$, $p < .06$, respectively, and for interword pauses from digit span, $\beta = -.36$, $p < .01$.

The introduction of the effectiveness predictors (aggregate spans) at Step 2 accounted for a significant additional portion of variance only in the prediction of word durations and interword pauses from nonword memory span, $\beta = -.24$, $p < .05$, and $\beta = -.25$, $p < .05$, respectively. Anxiety scores significantly explained 7% of variance in the preparatory intervals for both word and nonword span, $\beta = .28$, $p < .01$, and $\beta = .26$, $p < .05$, respectively.

Discussion

The results of this study provide interesting insights into the nature of individual differences in response timing patterns of serial recall in young children. The initial hypotheses were mostly confirmed by the results of the study, with predicted variations between the two time points and between the

Table 5
Regression analyses predicting response timing measures at T2

Step/Variable	Outcome variables																	
	PI word span[a] (N = 74)			IP word span[b] (N = 74)			PI digit span[c] (N = 75)			IP digit span[d] (N = 75)			PI nonword span[e] (N = 73)			IP nonword span[f] (N = 73)		
	B	SE B	β	B	SE B	β	B	SE B	β	B	SE B	β	B	SE B	β	B	SE B	β
Step 1																		
Age	–.01	.01	–.36**	–.01	.01	–.38**	–.01	.01	–.28*	–.01	.01	–.24*	–.01	.01	–.23†	–.01	.01	–.07
Art. rate	–.03	.02	–.17	–.01	.01	–.01	–.06	.02	–.35**	–.02	.01	–.36**	–.06	.03	–.24†	.01	.02	.06
Step 2																		
Age	–.01	.01	–.33**	–.01	.01	–.32*	–.01	.01	–.26*	–.01	.01	–.27*	–.01	.01	–.23	–.01	.01	–.09
Art. rate	–.03	.02	–.17	.01	.01	.02	–.06	.02	–.33**	–.02	.01	–.37**	–.06	.03	–.24†	.13	.02	.13
AS T1	.03	.02	.18	.01	.01	.02	.02	.02	.14	.01	.01	.32						–.25*
AS T2	–.03	.03	–.19	–.01	.01	–.16	–.03	.02	–.22	–.01	.01	–.26	.01	.04	.02	–.25	.03	
Step 3																		
Age	–.01	.01	–.35**	–.01	.01	–.33*	–.01	.01	–.26*	–.01	.01	–.27*	–.01	.01	–.20	–.01	.01	–.08
Art. rate	–.03	.02	–.19	.01	.01	.01	–.06	.02	–.33**	–.02	.01	–.37**	–.07	.03	–.27*	.02	.02	.11
AS T1	.03	.02	.17	.01	.01	.01	.02	.02	.14	.01	.01	.30	.					
AS T2	–.02	.03	–.10	–.01	.01	–.12	–.02	.02	–.20	–.01	.01	–.22	03	.04	.08	–.05	.03	–.21
Spence	.01	.01	.28*	.01	.01	.12	.01	.01	.03	.01	.01	.07	.01	.01	.26*	.01	.01	.17

Note. PI, preparatory interval; IP, interword pause; Art., articulation; AS, aggregate score.

[a] R^2 = .20 for Step 1 (adjusted R^2 = .18), ΔR^2 = .02 for Step 2, *ns* (R^2 = .22, adjusted R^2 = .17), ΔR^2 = .07 for Step 3, *ps* < .05 (R^2 = .29, adjusted R^2 = .24).

[b] R^2 = .14 for Step 1 (adjusted R^2 = .11), ΔR^2 = .02 for Step 2, *ns* (R^2 = .16, adjusted R^2 = .11), ΔR^2 = .01 for Step 3, *ns* (R^2 = .17, adjusted R^2 = .11).

[c] R^2 = .26 for Step 1 (adjusted R^2 = .24), ΔR^2 = .01 for Step 2, *ns* (R^2 = .28, adjusted R^2 = .24), ΔR^2 = .001 for Step 3, *ns* (R^2 = .28, adjusted R^2 = .23).

[d] R^2 = .28 for Step 1 (adjusted R^2 = .23), ΔR^2 = .03 for Step 2, *ns* (R^2 = .28, adjusted R^2 = .24), ΔR^2 = .005 for Step 3, *ns* (R^2 = .28, adjusted R^2 = .24).

[e] R^2 = .15 for Step 1 (adjusted R^2 = .12), ΔR^2 = .00 for Step 2, *ns* (R^2 = .15, adjusted R^2 = .11), ΔR^2 = .07 for Step 3, *ps* < .05 (R^2 = .21, adjusted R^2 = .17).

[f] R^2 = .006 for Step 1 (adjusted R^2 = –.02), ΔR^2 = .06 for Step 2, *ps* < .05 (R^2 = .06, adjusted R^2 = .02), ΔR^2 = .03 for Step 3, *ns* (R^2 = .09, adjusted R^2 = .04).

† $p < .06$.

* $p < .05$.

** $p < .01$.

different tasks. First, we briefly discuss the results related to the first four hypotheses, which aimed to replicate previous findings for this age range from both cross-sectional and longitudinal perspectives. Next, we present the main findings relating individual differences in age and trait anxiety to performance effectiveness (aggregate span) and performance efficiency (response timing measures and articulation rate).

We replicated the effect of age for both word and digit span accuracy measures (e.g., Alloway et al., 2006; Alloway, Gathercole, Willis, & Adams, 2004; Dempster, 1981) but not for nonword span. There are some suggestions in the literature (Alloway et al., 2006) that this measure increases steeply only after 6 years (the oldest age group in the current study had a mean age of 6 years 2 months).

The analysis of efficiency (which represented the focus of the current investigation) confirmed our first prediction based on previous findings in the literature regarding age and list length effects on response timing measures (Cowan et al., 1994; Cowan et al., 1998). There was a clear effect of list length, with children having longer preparatory intervals and interword pauses for LL3 than for LL2. As for the effects of age, at the second time point on both the word and digit span measures, children became more efficient on the same "strategic" segments of their recall output: preparatory intervals and interword pauses (but not word durations, which presented only minor age group effects). These segments could represent an index of executive processes characterized by anticipation and planning of response (both cognitively and as an overt output). The increase in their efficiency suggests that older children coordinate these processes more efficiently than younger children. Indeed, the 3- to 6-year age interval covered by this longitudinal study represents a period of considerable executive progress (see Zelazo, Carlson, & Kesek, in press, for a comprehensive review).

Analyses on interword pauses for both word and digit span at the first time point revealed an interesting age-related transition, partially contrasting with findings that have compared preschoolers with school-aged children (Cowan et al., 1994) or older groups of children or adults (Cowan et al., 1998). Older children from T1 (Age Group 2) had longer interword pauses (significantly for word span and marginally significant for digit span) than the younger age group. However, at T2, the situation followed the typical developmental pattern. The unexpected findings from T1 could suggest the presence of a utilization deficiency phenomenon (Bjorklund, Coyle, & Gaultney, 1992; Miller, 1990), namely, a "developmental lag between spontaneously producing the strategy and receiving any benefits from it" (Miller, 1990, p. 160).

One possible interpretation is related to the type of items that were used (words with two syllables). Cowan and colleagues (1994) compared two groups of children with mean ages of 4 years 5 months and 8 years 8 months and found that when short one-syllable words were analyzed, younger children presented longer interword pauses than older children (see Table 6 on p. 243 of that work). However, when looking at the medium-sized words (similar to the two-syllable words from the current study), a reversed age-related difference in the average interword pause was noted (younger children: $M = .30$, $SD = .25$; older children: $M = .34$, $SD = .39$). In the current investigation, however, this explanation alone cannot account for the reverse pattern of findings (longer interword pauses in younger children) that was observed using the same items at T2.

An alternative explanation takes into account the fact that interword pauses are thought to represent an index of covert memory search processes. The fact that these intervals became longer in the older sample at T1 could be indicative that this search had become more strategic, gradually approximating the pattern seen in older children and adults. It may be that in very young children the repetition of words represents a purely imitative (articulatory) process widely used in vocabulary acquisition (Gupta & MacWhinney, 1997). In older children, in the context of a goal-directed memory task, the process becomes more strategic and effortful, demanding additional executive resources. Factors related to practice effects might explain the increase in the interword processing efficiency of these children reassessed at T2. Finally, there might be some uninvestigated sample differences that would account for the documented (unexpected) decrease in the processing efficiency of Age Group 2 at T1; the issue of inherent sample differences places the importance of longitudinal studies over cross-sectional research (Baltes, 1968).

We addressed the second and third predictions regarding the mutual determination of performance effectiveness and efficiency in the regression models. The same strategic indexes of response timing (especially preparatory intervals) were also the best predictors of aggregate spans in the case of word and nonword memory span. In these tasks (with the exception of digit span), individual differences in key response timing measures made significant contributions to predicting aggregate span scores above the influences of age and articulation rate.

Looking at the converse relationship, memory span was a significant predictor only for the length of word durations and interword pauses from nonword span. However, in the case of word and digit span, the correlation matrix at T2 also revealed a negative moderate to strong relationship between aggregate span, on the one hand, and preparatory intervals and word durations, on the other. This confirms previous findings by Cowan and colleagues (1992, 1998). However, this predictive effect did not reach statistical significance in the regression models for the response timing measures from either word or digit span. This may be due to the restricted sample size and the fact that the effects of memory span might be partially overlapping with the effects of age.

The measure of articulation rate introduced at T2 did not contribute significantly to explaining variance in word and digit span above the effects of age. This is not necessarily surprising (Cowan et al., 1994; Gathercole & Adams, 1993; Rapala & Brady, 1990), although (as expected) this measure was positively associated with all aggregate span outputs. Ferguson and colleagues (2002) investigated different measures of articulation rate in relation to word and digit memory span in children from kindergarten to sixth grade. The results point to a similar overlap between variance in memory span accounted for by speech rate (for triple word pairs) and age (a 43.3% overlap using the variance partitioning method advocated by Chuah & Mayberry, 1999). It was, however, more interesting to note that articulation rate was a better predictor of nonword span. A possible explanation for the presence of articulation rate effects only for nonword span was put forward by Gathercole and Adams (1993) to account for similar findings in even younger children in the case of nonword span versus digit span. The authors suggested that it is implausible to presume that at this young age children are actively rehearsing only in the nonword span task but not in the digit span task. However, they speculated that these children's developing speech production skills might pose greater constraints on the nonword span measure than on the overlearned set of digits and very common words used in word and digit span tasks. Therefore, in young children, rather than representing an index of subvocal rehearsal, the measure of articulation rate might relate more closely to the spoken output from nonword span, reflecting "the common influence of a child's accuracy in planning and executing a sequence of articulatory gestures on the basis of a target acoustic representation" (p. 776).

The effects of trait anxiety were observed on both performance effectiveness and efficiency measures. In previous studies, digit span was proven to be overall less efficient (total response time) yet similarly accurate in high trait-anxious adults (Derakshan & Eysenck, 1998; Richards, French, Keogh, & Carter, 2000) and high state-anxious older children (9–10 years) (Hadwin et al., 2005). However, Darke (1988) found adult evidence for detrimental effects of anxiety on digit span for both performance effectiveness and efficiency. In the current investigation, anxiety represented an independent negative predictor of memory span across tasks (although only marginally significant for nonword span) and above its effects on efficiency measures. This result could have at least two possible explanations.

First, an "encoding" explanation would suggest a direct anxiety–processing effectiveness relationship. This type of explanation would claim that children with higher anxiety levels do not attend sufficiently to the presented stimuli and do not encode them efficiently, leading to deficits in recall. In the context of the span tasks, we would expect these encoding-related deficits to appear across measures but to be especially present on the nonword task, for which the encoding stage is particularly relevant, lacking the facilitative effects of word familiarity (from digit and word span). Thus, specific anxiety-related deficits during the encoding stage would lead to deficiencies in the redintegrative processing that takes place at retrieval (immediately before response production) (Hulme et al., 1999). Although there was a marginal effect of anxiety group on this task, it was weaker than the effect on word and especially on digit span. Difficulties during the encoding stage cannot alone account for the more pronounced anxiety-related deficit on digit span than on nonword span.

A second possibility, more interesting in the context of ACT predictions, is that the relationship between anxiety and processing effectiveness is influenced by processing efficiency. The second set of regression models indicates that anxiety has a significant impact on processing efficiency (preparatory intervals) from word and nonword span. In digit span, by looking at processing efficiency only at the subspan level (LLs 2 and 3), we might not capture the potentially stronger effects of anxiety on the higher segments of recall (LL4 and above). Support for this hypothesis can be derived from looking again at intertask relationships. For word and nonword span, we found strong relations between anxiety levels and efficiency indexes. For digit span, on which the analysis of LL3 response timing is clearly at the subspan level (mean aggregate span at T2 = 4.24, *SD* = 0.82), we found no independent contribution of anxiety to any efficiency measure. Therefore, it is possible that for digit span the detrimental effects of anxiety on performance efficiency may take place only at higher levels of task difficulty (not evaluated in the current investigation), leading to the deficits that we found in the performance effectiveness of high-anxious children.

Conclusions

Towse and Hitch (2007) summarized the critical sources of memory variation in developing children as follows: the rate at which information can be processed, the children's ability to perform dual tasks, the timing of these processes, and the parameters that describe specific memory subsystems at different ages. This perspective reflects a general trend in short-term memory research characterized by a shift in emphasis from a "chunk limit" to a "time limit" (Cowan, 2007). The microanalysis of response timing indexes proposed by Cowan and colleagues challenges and refines the view of a global development in processing speed to include the maturational timetable of different executive processes associated with the increase in memory span. In adults, the duration of preparatory intervals and interword pauses are considered to reflect covert memory search, planning, and response monitoring as well as redintegration processes (Hulme et al., 1999).

In the current study, a similar yet more complex picture emerges. In time, preschoolers become more efficient in the key segments of their response (interword durations and preparatory intervals). However, a more important part at this age appears to be played by preparatory intervals, with this being reflected in their association with span accuracy. The interword pauses appear to undergo a temporary slowing during the 5- to 6-year age interval, which is compensated for 8 months later, approximating the developmental trends found in older children (although the possibility of sample differences at T1 and the longitudinal results from T2 undermine the strength of this unexpected cross-sectional finding). However, nonword span remains more constrained by the children's developing speech production skills, also indexed by the measure of articulation rate.

It is for future research to examine the exact nature of the relationship among trait anxiety, span efficiency, and effectiveness. Our results have revealed that at this age a higher level of trait anxiety predicts (a) lower effectiveness on all span tasks (especially on digit span) and (b) lower efficiency in children's preparatory intervals (in the case of word and nonword span). Higher anxiety levels might interfere with encoding processes and/or generate task-related efficiency impairments (clearer at a span level than at a subspan level), thereby supporting the predictions of ACT. Cowan and colleagues (2006) warned that even in typically developing children, the speed of processing could be just a marker of memory development without being a causal variable. Future research should investigate the impact of anxiety on span effectiveness either through its impact on efficiency or by directly interfering with memory processes.

There are a number of limitations in the current investigation that could also inspire future research in this field. First, it is fruitful to employ a true microgenetic design and to closely follow up children for even shorter periods of time than the 8 months. To our knowledge, no microgenetic study has also employed the microanalysis of response timing, although it has been proven to generate valuable hypotheses regarding the underlying processes and memory strategies. It would be useful to analyze the differences in children's recall timing across subsequent trials in a modified microgenetic design such as the one proposed by Coyle and Bjorklund (1996). However, in the memory span design, this would require more trials for each list length and would be more appropriate for older children, who also present higher spans.

The effects of trait and state anxiety should be examined more systematically, with the assessment of anxiety levels at all time points. In their review, Weems and Stickle (2005) suggested that even for children measures of trait anxiety show remarkable stability over time, although for the preschool age a trend toward a decrease in parental reports of anxiety symptoms has been noted (Spence et al., 2001). Although it is desirable to relate measures of both trait and state anxiety to the cognitive outcome (Miu, Miclea, & Houser, 2008), state anxiety cannot be reliably assessed via self-reports in children until 7 or 8 years of age (Schniering, Hudson, & Rapee, 2000; Stone & Lemanek, 1990). In the current investigation, we relied on the assumption that high trait-anxious preschoolers, faced with a potentially stressful situation (e.g., the evaluation of performance on a cognitive task) presented higher levels of state anxiety (Hadwin et al., 2005; Lau, Eley, & Stevenson, 2006), although the lack of a direct measure of state anxiety remains a limitation of the study (and of most studies involving young children) (Stone & Lemanek, 1990).

The current study has revealed that the 3- to 6-year age interval could represent a critical developmental window during which the efficiency trajectories of low-anxious and high-anxious children are starting to diverge. It is also a time period during which developmentally tuned interventions could make a difference. Cowan and colleagues (2006) showed that simply training children to "speed up" their responses did not affect their overall span accuracy. However, in high-anxious children, it might be considered as a useful strategy to be taught early on. This intervention and other interventions targeting processing efficiency, rather than processing effectiveness, could enable them to prevent the efficacy deterioration that undermines overall performance in complex, executive-demanding memory tasks.

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