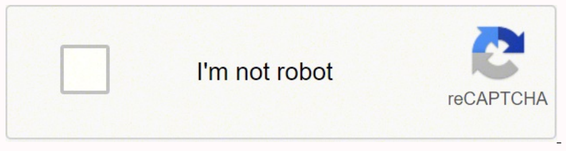

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Items then must be extracted from a passively maintained (i.e., “activated”) memory trace at the time of recall. The disadvantage of that approach is similar to the disadvantage of a snowball that has grown beyond control and continues to plunge downhill. The latter could describe the episodic buffer of Baddeley (2000, 2001).Finally, in addition to providing options for the cleaner measure of what is important within WM, the present study allows a fresh look at the demands of various WM tasks, including capacity demands that are intentionally tapped and specific skills that are unintentionally tapped by WM measures. [Google Scholar]Sperling G. [Google Scholar] This second component is not clear in the means, given some residual benefits of attention on digit span in young children. A hit rate of 1.0 or nearly so could occur primarily because of a strong bias toward guessing, “yes, there has been a change.” One further suspects that a hit rate of nearly, but not quite, 1.0 would be almost as problematic within this approach.In the revised formula described by Cowan (2001) it is assumed, as by Pashler, that k items can be apprehended. [PubMed] [Google Scholar]Atkinson RC, Shiffrin RM. [PubMed] [Google Scholar]Todd JJ, Marois R. Quarterly Journal of Experimental Psychology (A) 1973;25:104–111. A color could be used more than once in an array so that the location of colors, and not merely their inclusion or omission from the array, had to be remembered for successful performance. The WM variables were entered into the regression individually, but with all variables of the same type in a single step. Working memory span and the role of proactive interference. (1) These WM tasks correlate highly with aptitudes even when the domain of the processing task (e.g., arithmetic or spatial manipulation) does not match the domain of the aptitude test (e.g., reading) (Daneman & Merikle, 1996; Kane et al., 2004). 3–18. Poster presented at the annual convention of the Psychonomic Society. [Google Scholar]Cowan N, Lichty W, Grove TR. Visual similarity effects in immediate verbal serial recall. [Google Scholar]Vogel EK, Machizawa MG. We discuss these.Attention is a controversial concept but large-scale treatments of it can be found in the literature (e.g., Cowan, 1995; Luck & Vecera, 2002; Näätänen, 1992; Pashler, Johnston, & Ruthruff, 2000; Shiffrin, 1988). Studies in long-term memory. 2000;52:629–651. A main type of strength is their strong correlation with intellectual aptitude tests, and a main type of weakness is the difficulty encountered in analyzing and interpreting WM test results. The non-significant chi-square and fit statistics indicate a good fit. The false alarm rate FA may be influenced by the number of items for which no memory trace is available, N-k. Cowan (2001) summarized many phenomena that appeared to meet these criteria and produced convergent capacity estimates. Second, Bleckley, Durso, Crutchfield, Engle, & Khanna (2003) found that high-operation-span individuals were able to allocate attention to a ring in which a target was expected to appear, excluding the area inside of the ring, whereas low-span individuals allocated attention as a solid disk that included the irrelevant area inside of the relevant ring. The instructions indicated that the digits should be ignored until the recall probe because they might prove to be distracting otherwise, and that the participant should then just make his or her "best guess" as to the identity of the digits. [Google Scholar]Lovett MC, Reder LM, Lebière C. VIII. Thus, decay of the relevant sensory memory trace was much slower in audition. One way to tell if a general resource exists is to determine whether dual-task interference can be obtained using two tasks that share nothing in the way of more specific processes but, of course, that criterion is difficult to meet with assurance. British Columbia, Canada: Vancouver; 2003. The highest correlations were obtained with digit span, which was only a mediocre predictor of aptitude in adults.Experiment 1, Correlations Between Working-Memory and Scholastic Measures in Children, and Reliability EstimatesDSCSLSRSISVACCCVCQDigit Span (DS).88.41.51.68.67.36.64Counting Span (CS).35*.66.64.35.23.37.24Listening Span (LS).44*.48*.75.32.31.42.53Running Span (RS).61*.30*.30*.88.68.35.47Ignored Speech (IS).50*.14.20.51*.68.28.41Visual Arrays (VA).28*.25*.30*.27*.18.61.54CAT Composite.52*.15.37*.38*.31*.38*.84 Verbal.55*.18.47*.38*.32*.29*.82* Quantitative.48*.20.31*.41*.26*.44*.90*.72* Nonverbal.36*.05.25*.25*.24*.86*.52*.66*The visual-array capacity correlated with the CAT at about the same level when capacity was based on trials with changes to a unique color (r = .31) or a non-unique color (r = .38). 1996;24:70–82. [Google Scholar]Cowan N. New York: Wiley; 1949. Storage-and-processing tasks are complex but dominate the WM literature, we believe, largely because each new study can rely on past findings with those tasks. 2001;130:184–198. A history of psychology in autobiography. The first method is reported in Appendix B. From these figures it is possible to calculate how much of the predictive abilities of the storage-and-processing measures were shared by the scope-of-attention measures. One person might excel in storage and another in processing, yet both might obtain the same score on a storage-and-processing type of WM task. Even with age partialled out, most WM measures correlated with most aptitudes (though there were exceptions). In contrast to the ignored-speech condition, it can be seen that the number correct did not remain constant across list lengths, but grew with list length. Working memory, short-term memory, and general fluid intelligence: A latent-variable approach. Hove, U.K: Erlbaum; 1993. Session 1 was about 1.5 hours in duration, and Session 2 lasted about 1 hour. Set-size effects in primary memory: An age-related capacity limitation? (1999) judged the capacity of memory with short test delays and found that it was about 3.5 items in adults, regardless of the list length, and smaller in children.In the main procedure of Cowan et al. Operational efficiency and the growth of short-term memory span. They have been based on the premise that processing and storage both tap a common resource (see Daneman & Carpenter, 1980). 1997;390:279–281. Closely-related work also emphasizes that stimulus complexity limits the capabilities of executive control at a particular level of cognitive maturation (cf. We argue that the critical aspect of successful WM measures is that rehearsal and grouping processes are prevented, allowing a clearer estimate of how many separate chunks of information the focus of attention circumscribes at once. 1991;2:271–274. 28–61. [PubMed] [Google Scholar]Wheeler ME, Treisman AM. Cognitive complexity and control: II. The only measures that correlated significantly with both of these practical scholastic criteria were counting span, running span, and memory for ignored speech, and perusal of the table shows that this was not the result of uniformly high reliabilities for these particular variables.Table 4 shows correlations within children. Table 8 shows correlations after age-group variance was partialled out, reliabilities of the measures, and, above the diagonal, age-partialled correlations based on attenuation-corrected raw correlations. [Google Scholar]Baddeley AD, Logie RH. Time constraints and resource sharing in adults’ working memory spans. Each square was 0.75×0.75 degrees in visual angle. Memory. This table yields quite a different pattern than was obtained in the adults. The model shown above is consistent with the idea that storage-and-processing and scope-of-attention measures essentially measure the same construct, presumably the capacity or scope of attention.Structural equation model of performance in Experiment 2. 1989;70:77–97. 2001;130:169–183. However, the advantage in prediction of high school grades, and of the CAT in children, favored the scope-of-attention measures (.18 and .24, respectively) over storage-and-processing measures (.13 and .14, respectively). Three practice trials were followed by 27 test trials.In the visual-arrays task, the procedure was the same as in Experiment 1 except for the selection of set sizes. [Google Scholar]Nairne JS. This we attribute to the absence of efficient rehearsal and grouping in the younger children. Other laboratories, as well, have begun to experiment with a variety of new WM procedures, some of which do not involve a dual task (e.g., Oberauer, Süß, Wilhelm, & Wittmann, 2002).In the literature, there appears to be no theoretical framework allowing performance on all of these WM tasks to be understood. Oxford: Clarendon Press; 1986. Tehan & Humphreys, 1995), and that type of intrusion conceivably could be larger when there is a one-to-one correspondence between serial positions in the various lists because it could increase the structural similarity of the lists.Figure 2 shows the means separately for each set size, for the third-grade children (top panel), fifth-grade children (middle panel), and adults (bottom panel). [Google Scholar]Usher M, Haarmann H, Cohen JD, Horn D. The targets to be counted were dark blue circles, which were mixed with some dissimilar distractors (red squares and circles). The two largest portions of variance were those shared between all measures (.11) and those unique to the storage-and-processing measures (.10), with a somewhat smaller amount shared between storage-and-processing and scope-of-attention measures (.05).Experiment 1, prediction of ACT composite score in adults, conjointly by subsets of three types of WM variable. The tones were played one at a time with a stimulus onset-to-onset period of 400 ms. 1990;14:151–171. Third-grade children began with two practice trials at each list length. Cognitive Science. The same was true of auditory sequences.Regression analyses were carried out in a manner comparable to Experiment 1. 2001;130:208–223. The power of numerical discrimination. Performance in that task was virtually identical across trials with 5, 6, or 7 response slots and the results were therefore collapsed across this variable.In order to score all procedures in a manner that was as conceptually equivalent as possible and estimated capacity, two methods of span scoring were used. If one assumes that storage-and-processing measures are useful because they tap into attentional control, these measures therefore still should correlate with measures of the scope of attention.Cowan (1995) reviewed literature suggesting that the scope of attention does not rely primarily upon frontal lobe mechanisms as the control of attention does but, rather, upon parietal lobe mechanisms. Hillsdale, NJ: Erlbaum; 1998. Journal of Experimental Psychology: Human Learning and Memory. [Google Scholar]Graesser A, II, Mandler G. Covert processes and their development in short-term memory. 1871;3:281–282. New York: Academic Press; 1974. For example, the interpretation offered by Daneman and Carpenter was that the reading-or listening-span memory score measures how much capacity is available when combined with linguistic comprehension, and therefore provides an index of the efficiency of that comprehension. It is clear from this figure that digit span increased beyond the range of the other measures. Using working memory theory to investigate the construct validity of multiple-choice reading comprehension tests such as the SAT. In the second experiment, we included two measures of verbal ability, the Peabody Picture Vocabulary Test (PPVT: Dunn & Dunn, 1997) and the vocabulary subtest of the Stanford-Binet Intelligence Scales (Thorndike et al., 1986), and two measures of nonverbal ability, Raven's Progressive Matrices (Raven et al., 1998) and the pattern analysis subtest of the Stanford-Binet scales. For simple spans, there is the expectation of developmental changes in this regard. The task was to listen to each sentence and determine if it was true or not. Elliott, Louisiana State University.J. Scott Saults, University of Missouri - Columbia.Candice C. 2003:884–889. [PubMed] [Google Scholar]Daneman M, Carpenter PA. The same procedure was then repeated with six boxes, and then seven, for a total of 27 test trials. The table also shows that, corrected for attenuation, all of the correlations between visual arrays and other WM measures in adults fell within the range of .32 to .48. The possibility of coherence with other research comes from an adjustable-attention hypothesis in which the focus of attention can zoom in to hold on to a goal and the minimally-required additional data, as in recent studies by Engle and colleagues (e.g., Kane et al., 2001), or zoom out to apprehend (retrieve into the focus of attention) a field of items.The primary expectation of the present study was that scope-of-attention tasks would be predictive; more specifically, (a) that a substantial amount of variance would be shared between storage-and-processing tasks, on one hand, and scope-of-attention tasks, on the other, and (b) that this shared variance would predict intellectual aptitudes. [Google Scholar]Salthouse TA. 1960;74 (Whole No. 498) [Google Scholar]Stevanovski B, Jolicoeur P. In visual-array comparisons, note that the value of 8.22 in adults is not out of line with expectations; according to the capacity formula explained in Appendix A, 75% correct on a set size of 8 items corresponds to a capacity of 4.0 items.Nelson Cowan, University of Missouri – Columbia.Emily M. George A. There were no tradeoffs between the visual and auditory tasks; no indication that individuals scoring better on memory for ignored speech did worse on the rhyming task, nor any indication within participants of better speech memory on trials with poorer rhyming-task performance (see Cowan et al., 2002). 1995;102:211–245. Nature Neuroscience. The model is explained in detail in Appendix A. We considered that it differs from the ignored-speech and running-span measures in two ways: (1) its memoranda are nonverbal rather than verbal in nature, and (2) they are presented visually and spatially rather than aurally and sequentially. There was a 1-s gray screen (like the background of the arrays) between the offset of the first array and the onset of the second array. Meanwhile, lists of spoken digits were to be ignored. 2003;26:709–777. We argue that, in order to measure WM capacity on a common scale, it is necessary to consider the scope of attention instead of its control.Theoretical work on information processing has long been divided on the role of attention in short-term storage. 2002;131:48–64. Each screen included 3 to 9 targets, 1 to 5 circular distractors, and 1 to 9 square distractors, which varied independently. The generality of working- memory capacity: A latent-variable approach to verbal and visuo-spatial memory span and reasoning. This worked well, given that the most recent item was the one most often correct. Incentives for participation included course credit for adults and a book plus $10 for children.The digit-span task was as before except that only one span run was conducted, and with only three trials per list length instead of four. Individual differences in working memory and reading. This is the first of several ways in which digit span can be distinguished from the measures in which it is not as easy to use attention to advantage during encoding.Experiment 1, mean number of items correct at each set size in each task (graph parameter) for third-grade children (top panel), fifth-grade children (middle panel), and adults (bottom panel). Session 2 included (5, 6) two runs of a digit-span task (followed by a rapid-speaking task that will not be reported here) and, finally (7) a task involving memory for ignored speech. Morey and Cowan found that recitation of a random 7-digit memory load did impair performance, presumably because that task taxes attention.Cocchini et al. Attention and brain function. Journal of Experimental Psychology: Human Perception and Performance. 1998;39:195–217. For example, one possible basis of the higher predictive value of storage-and-processing tasks as opposed to single tasks such as digit span is not the inclusion of processing per se, but rather the fact that the processing component interrupts covert verbal rehearsal (cf. [PubMed] [Google Scholar]Sokolov EN. Working memory and language comprehension: A Meta-Analysis. However, as we will discuss, it is far from clear how the storage-and-processing tasks are carried out, what aspects of the tasks account for the high correlations with aptitudes, and whether all such WM tasks operate similarly.There have been a number of studies applying the logic of storage-and-processing types of tasks and other complex WM tasks in childhood development (e.g., Ashcraft & Kirk, 2001; Bayliss, Jarrold, Gunn, & Baddeley, 2003; Case et al., 1982; Daneman & Hannon, 2001; Gathercole & Pickering, 2000; Hitch, Towse, & Hutton, 2001; Kail & Hall, 2001; Swanson, 1996; Towse Hitch, & Hutton, 1998). 1999;91:660–668. Each digits was scored as correct only if it was recalled in the correct serial position, so memory of the binding between digits and serial positions in the list was required for correct responding.The digit list length was individually adjusted and four list lengths per individual were used: a length equal to the participant's predetermined digit span (using attended lists), and lists 1, 2, or 3 digits shorter than that. A cognitive complexity metric applied to cognitive development. Conceptual span yielded higher correlations than reading span in the prediction of aspects of reading comprehension that required unconnected semantic elements to be retained (e.g., verbal problem-solving; anomaly detection). They are (1) that scope-of-attention tasks will be predictive, i.e., will both correlate with storage-and-processing tasks and prove useful in predicting scholastic and intellectual aptitudes; (2) that additional predictive ability of the conventional, storage-and-processing tasks can be traced to specific skills, not general WM; and (3) that, in children too young to rehearse, even simple digit span will yield high correlations with aptitudes. 1990;18:251–269. [PubMed] [Google Scholar]Baddeley A, Hitch GJ. As in Variant 1, in Variant 2 there were 27 test trials.The visual array comparison task was adapted from Luck and Vogel (1997). In: Miyake A, Shah P, editors. However, for young children, who cannot engage in sophisticated rehearsal strategies (Flavell et al., 1966), simple span tasks may well serve as adequate measures of the scope of attention.The success of storage-and-processing spans may not be for exactly the presumed reason (e.g., Daneman & Carpenter, 1980). Raw correlations between the two types of measures (Table 7) were all significant and remained so with age partialled out (Table 8). There were four test trials presented at each list length and then the length increased by one item, a process that was repeated until the participant made an error on each of the four lists at a particular length, or until the maximum length of 9 items was reached. Cambridge: Cambridge University Press; 1999. 2004;15:634–640. Human memory: A proposed system and its control processes. 1970;32:301–345. Attention. Stevens' handbook of experimental psychology. Unlike any other WM measures, two of the three scope-of-attention measures (auditory-sequence and visual-array comparisons) were correlated with all four aptitude tests. This may account for the difference in effects of the load in the two studies.It might still be theoretically possible that the verbal and nonverbal tasks of Morey and Cowan (2004) share some mechanism other than attention. Second, the scope-of-attention measures tended to have an even profile across verbal and nonverbal aptitude measures (Figure 6). [PubMed] [Google Scholar]Cocchini G, Logie RH, Della Sala S, MacPherson SE, Baddeley AD. Given that the process of retrieving items from an unattended auditory or phonological stream into a categorized form is quite difficult, there is room for proactive interference between trials (cf. 1994;33:234–250. For children, each test trial block included one trial each at List Lengths 2, 3, 4, and 5, in that order. Mukunda and Hall (1992) carried out a meta-analysis of the within-age correlations in adults and children between various WM tasks and various intellectual aptitude tasks, and found that one measure, running memory span (11 tests, R = .40) performed about as well as reading span (11 tests, R = .43) and better than operation span (6 tests, R = .23), counting span (3 tests, R = .28), or digit span (53 tests, R = .22). (1999). Journal of Experimental Psychology: Learning, Memory, and Cognition. However, it is assumed that if there is no change between the two arrays, and if the cued item happens to be an item that is included within the set k that the subject apprehended, then that knowledge will allow the subject to answer correctly that no change has occurred. Nevertheless, in both modalities, the whole-report limit was about 4 items. Presumably, then, memory of the squares is not assisted by a verbal rehearsal process. [Google Scholar]Baddeley AD. Theoretically, the act of recall may interfere with the activated-memory record (Cowan, Saults, Elliott, & Moreno, 2002), or there may be a phenomenon analogous to inhibition of return (Posner, Rafal, Choate, & Vaughan, 1985), which can occur not only for spatial locations but also for previously-attended objects (Tipper, Driver, & Weaver, 1991).For unattended auditory sequences, the acoustic memory record persists for a number of seconds (Cowan et al., 1990, 2000; Darwin et al, 1972; Glucksberg & Cowen, 1970; Norman, 1969). By attracting attention to the sensory memory of the list only after it ended, rehearsal and grouping of the list during its presentation could be minimized and memory performance (recall of digits by keypress) presumably was based on the post-hoc conversion of items from an auditory sensory memory record into a categorical form in the focus of attention. [PubMed] [Google Scholar]Henry LA. The interaction of age×condition did not approach significance, p > .1. (By our calculations, in Study 1 of Kail and Hall these correlations were, for letter and word spans, .17 and .27; for reading and listening spans, .30 and .25. Another was that predictive variance unique to the storage-and-processing measures will tend to reflect specific skills rather than WM capacity per se. The participant answered by pressing one computer key to indicate that the color changed between arrays (the “/” key) and another key to indicate that it did not change (the “z” key). The first of these was the topic of previous work (especially Cowan, 2001; Cowan, Chen, & Rouder, 2004) whereas the other three are topics of the present investigation. We both propose that a zoomed-out setting has more breadth or covers more objects, but has less intensity or precision of processing of each object, than a zoomed-in setting. This interpretation can help to account for a wide range of findings. The main analyses are shown in Table 9. Figure 7 shows that the largest portion of variance in g (.28) was shared between all three types of WM measures. Evidence for a visuo-spatial scratch-pad in working memory. In the table, ΔR2 values for each step are shown along with statistical significance of these values. The basic idea is that, if the participant recalls the color of the square in the first array that was at the location corresponding to the encircled square in the second array, then he or she answers correctly; otherwise, he or she guesses. The central picture kept changing whereas the peripheral pictures remained the same throughout each sequence leading to an auditory memory trial, and then changed as the rhyming game resumed. Numbers within the overlapping sections of the circles do not represent collinarity between the variables, but portions of high school grades variance that are predicted in common by the WM variables shown as overlapping.A further analysis of the portion of high school grades variance uniquely predicted by scope-of-attention measures (.09) indicated that .06 of this variance was attributable uniquely to the two verbal measures (running span and ignored speech), .04 was unique to visual-array comparisons, and none was shared among all three. The numbers shown above the diagonal were calculated by starting with attenuation-corrected correlations and partialling out the age effect to yield the best estimate of within-age relations. Child Development. Memory while shadowing. 62–101. Binding in short-term visual memory. At an estimated viewing distance of 50 cm, the array fell within 9.8 degrees horizontal×7.3 degrees vertical visual angle of view. 1959;57:137–146. 235–286. The different pattern of correlations with these two main scholastic criteria is intriguing. A further examination shows that the largest portion was that shared between scope-of-attention tasks and digit span, though a substantial portion was shared between all of the tasks (.07).Experiment 1, prediction of within-age variance in CAT composite score in children, conjointly by subsets of three types of WM variable. There has been some concern that the feature of the processing task that impairs memory performance is the imposition of a time delay during which rehearsal is impossible (Towse, Hitch, & Hutton, 1998) or the imposition of high-frequency retrievals or processing during which rehearsal is impossible or storage is somehow interfered with (Barrouillet, Bernardin, & Camos, 2004; Saito & Miyake, 2004). [PubMed] [Google Scholar]Kane MJ, Engle RW. The task was to recall the digits from the last spoken list in the order in which they were presented. It must be assumed (1) that the objects or chunks of information recalled are identifiable, (2) that the activation of features persists long enough for the maximal extraction of information into the focus of attention, and (3) that the focus of attention does not engage in multiple cycles of retrieval-and-recall from the field of activated features on one trial. Performance fell off as a function of the number of squares in the array above 3 or 4.A simple model of performance (Cowan, 2001) can be used to estimate how many of the squares from the first array were held in WM. It leads to the advocacy of certain relatively simple WM tasks that might be more easily interpretable than storage-and-processing tasks.A Theoretical Framework for WM-Capacity Measurement Based on Adjustable Attention Exposition of the theoretical framework depends on an understanding of (1) the work that has been done to link attention to WM, (2) the reasons why that work has not yet produced a meaningful scale of WM capacity for use in examining individual differences in aptitude, and (3) theoretical underpinnings for constructing such a meaningful scale. These measures appear to correlate more highly with vocabulary measures than with at least one of the nonverbal measures. However, the present results indicate that this generality extends to at least some comparisons between dual-task and single-task measures of WM.To capture considerable variance in aptitudes in more mature participants, it appears necessary that the WM task include processing impediments to rehearsal and grouping, presumably because performance is then based on the scope of attention (Cowan, 2001). Three two-sentence practice trials were followed by three blocks of test trials using the same list lengths and same number of trials as in counting span.Scope-of-attention tasks The running memory span task was a modification of one developed by Cohen and Heath (1990). [PubMed] [Google Scholar]Cowan N, Nugent LD, Elliott EM, Saults JS. Each trial was initiated by the participant’s keypress. Mathematical model for the transition rule in Piaget's developmental stages. 1–49. 2001;130:621–640. 2002;109:376–400. Two separate verbal processing rates contributing to short-term memory span. [PubMed] [Google Scholar]May CP, Hasher L, Kane MJ. From this figure, one can see that the role of digit span was greatly diminished when age-related variance was not included. Hillsdale, N.J: Erlbaum; 1992. Working memory retention systems: A state of activated long-term memory. Visual-array comparisons were an exception in that they involved visual arrays to be remembered, and did not correlate with either high school grades or ACT scores in Experiment 1. This sort of question can be investigated by creating Venn diagrams of the portions of variance shared between three types of predictors (digit span, storage-and-processing measures, and scope-of-attention measures), shared between pairs of them, and unique to each type. Processing capacity defined by relational complexity: Implications for comparative, developmental, and cognitive psychology. [Google Scholar]Hitch GJ, Towse JN, Hutton U. The left-hand column of regressions is the prediction of g by WM measures, whereas the right-hand column is the prediction of g by WM measures age group variance is removed.Experiment 2, Stepwise Regressions Predicting g From Three Types of WM MeasureTargeted VarianceStepPredictorsgwithin-age portion of g0age group--.66**1storage and processing.56**.08**2scope of attention.04**.023digit span.02*.002digit span.03**.003scope of attention.03*.011scope of attention.45**.06**2digit span.06**.013storage and processing.10**.03**2storage and processing.15**.03**3digit span.02*.001digit span.35**.03**2storage and processing.24**.06**3scope of attention.03*.012scope of attention.17**.04**3storage and processing.10**.03**The results of the analyses have been synthesized into Figure 7 and Figure 8. All of the boxes were to be filled on each trial. Miyake et al. Neural mechanisms of general fluid intelligence. For the present Experiment 1 data set (including all age groups), using the revised method, the mean (and SD) capacity estimates for displays of 4, 6, 8, and 10 items, respectively, were 2.78 (0.95), 2.97 (1.62), 3.30 (2.02), and 3.21 (2.09) items. [Google Scholar]Gobet F, Simon HA. Memory and Cognition. Working memory capacity and distractibility in children. 29–50. It theoretically could be a visuospatial form of rehearsal. suggested that their data could be explained without reference to a cross-domain resource. We then discuss theoretical implications, including remaining issues that the present study cannot resolve. [Google Scholar]Engle RW, Tuholski SW, Laughlin JE, Conway ARA. [Google Scholar]Cowan N, Towse JN, Hamilton Z, Saults JS, Elliott EM, Lacey JF, Moreno MV, Hitch GJ. One might think that running memory span possibly could be carried out through a very active process in which the participant retains the most recent k items and continually updates the retained set by dropping the least-recent item to make room for the newest item. Baddeley, 1986) and thereby allows other processes to play a dominant role. Yet, there is not much agreement in the field as to the definition of WM, the best measures to examine it, or why these measures work (e.g., see the differences of opinion within the chapters of Miyake & Shah, 1999). [Google Scholar]Shiffrin RM. Cowan, 2001), including diverting attention, making sequences rapid and unpredictable, and presenting a brief array of items.Diverting attention Attention can be diverted from the stimuli to be remembered during their presentation. In particular, all but one of our storage-and-processing and scope-of-attention WM measures involved auditory or phonological sequences to be remembered, and resulted in correlations with at least some aptitude measures in both younger and older participants in both experiments. British Journal of Developmental Psychology. [PubMed] [Google Scholar]Cowan N, Chen Z, Rouder JN. We also have shown that digit span correlates well with aptitudes in younger children, but not in older children or adults. As in Experiment 1, this supports the notion that digit span provides an impure measure of WM capacity not specifically because it fails to include a dual task (as the scope-of-attention tasks do not include one, either), but because it allows covert verbal rehearsal and grouping of items. In Session 2, on a different day, tasks were carried out in the order: PPVT, Raven's Standard Progressive Matrices, a rapid-speaking task that will not be described here, and running memory span. Concurrent performance of two memory tasks: Evidence for domain-specific working memory systems. The task was to indicate whether the arrays were the same or different. A better-controlled example is the classic study by Sperling (1960), who presented an array of characters to be recalled. A reevaluation of working memory capacity in children. However, this procedure is likely to produce a very high level of proactive interference from the large number of stimuli within each trial.Last, we examined four age groups (not only three), yielding a widened age range, clear age trends, good estimates of within-age-group variance, and older children who could use rehearsal.Only participants who attended two sessions and, in those sessions, completed all WM tests were included in the final sample. It then proceeded to 12 trials at that set size (6 with a change in color and 6 with no change). It is the number of objects or chunks that can be extracted and held at one time in the focus of attention that we hope to measure.There are assumptions that must be met before it can be assumed that this use of attention during retrieval will provide a meaningful measure of the scope of attention. This seems inconsistent with the view that the cause of a limited capacity is insufficiency in the duration of the temporary memory record upon which attention is focused.The third assumption has to do with retrieval from activated memory into the focus of attention. Hillsdale, NJ: Erlbaum; 1978. 1997;126:211–227. Long-term working memory. Working memory and language. 2001;44:339–387. Psychonomic Bulletin & Review. The theoretical suggestion was that digit span is higher because there is no secondary task (as in the storage-and-processing spans) or built-in processing difficulty (as in scope-of-attention tasks) to interfere with the functioning of attention during reception of the list, including (but not limited to) rehearsal and grouping of items.There is reason to believe that even the youngest children carry out some function of attention during presentation of the lists in digit span, though not rehearsal. Testing began with 4 practice trials with 2-item arrays. Control conditions and experiments establish both of these points. Miller's (1956) discussion of the finding that people could retain only about 7 items also seems neutral to the involvement of attention in short-term retention. Psychological Review. Given that young children do not engage in much covert verbal rehearsal, or do so only inefficiently (e.g., Cowan et al., 1994; Cowan & Kail, 1996; Flavell, Beach, & Chinsky, 1966; Gathercole, Adams, & Hitch, 1994; Guttentag, 1984; Henry, 1991; Hulme & Muir, 1985; Ornstein & Naus, 1978), the superiority of storage-and-processing tasks for young children could be called into question.It can be argued that the storage-and-processing measures are theoretically ambiguous. [PubMed] [Google Scholar]Dunn Lloyd M, Dunn Leota M. 1980;19:450–466. 2001;24:87–185. However, a simpler hypothesis is that retrieval into the focus of attention is fixed across modalities, at about 4 separate items in the typical, normal adult.Insensitivity to stimulus array duration Second, in several array procedures (e.g., Luck & Vogel, 1997; Sperling, 1960) the duration of the array has been varied from less than 100 ms to about a half second, with little or no change in the resulting memory limit. The classic example of this sort of technique is running memory span (Pollack et al., 1959), which will be analyzed at greater length shortly.Spatial array Last, a spatial array of information containing too many items to be apprehended at once can be presented. Individual differences in semantic short-term memory capacity and reading comprehension. It is beyond the scope of this article to review the many convergent procedures examined in these reviews but, later, the principles will be illustrated with three such tasks used in the present study. Each list was preceded by a yellow-bordered box with the word “READY” for 1 s. There may be other portions of variance related to specific skills required by a particular measure, especially in the storage-and-processing measures, given that they each include a separate processing component; but our research goal is to determine if there is nevertheless considerable common variance among tasks that can be attributed to the scope of attention.The control-of-attention and scope-of-attention hypotheses are not necessarily in conflict. It seems likely that the portion shared with digit span reflects a specific linguistic WM ability such as facility with phonological materials (Gathercole & Baddeley, 1993).We propose that the portion of predictive variance shared between storage-and-processing measures and scope-of-attention measures reflects the scope of attention. 2001;24:151–152. Luck and Vogel (1997) found no effect of a 2-digit memory load on visual-array comparison performance. [PubMed] [Google Scholar]Bentin S, Hammer R, Cahan S. The mental effort requirement of cumulative rehearsal: A developmental study. Kane and Engle (2002) reviewed evidence converging on this point. For listening span, it may occur not only for the same reason but also because of a more general linguistic influence; the sentences may be used as cues to recall of the sentence-final words (Cowan, Towse et al., 2003).Experiment 2, correlations between each WM variable and four aptitude tasks (Peabody Picture Vocabulary Test, Stanford-Binet Vocabulary subtest, Ravens Progressive Matrices, and Stanford-Binet Pattern Analysis subtest), based on attenuation-corrected raw correlations (top panel) and partial correlations, with age partialled out, based on attenuation-corrected scores (bottom panel).Counting span is the measure with the highest correlation with nonverbal aptitude measures, although the three scope-of-attention tasks have the most even profiles across measures. Raw correlations are under the diagonal, which shows the reliabilities of the measures. (4) Latent variable analyses (Conway et al., 2002; Engle et al., 1999) show that the portion of the variance in storage-and-processing WM tasks that is most responsible for its correlation with aptitude tests is not the portion that is in common with simple list-recall span tasks, but the portion unique to the storage-and-processing tasks. It might be possible to account for these results with a theory in which the auditory modality has both slower sensory decay than vision and, for some reason, commensurately slower retrieval of information from sensory memory. The digits 1–9 were digitally recorded in a male voice and compressed to fit within a quarter-second time window, without a change in fundamental frequency, using the SoundEdit 16 program (Macromedia, Inc., San Francisco, CA). Regarding residual attention, there was a control condition in which there was no rhyming task and the digit lists were attended (Figure 1, dashed lines). An instance theory of attention and memory. 2003;132:71–92. After several screens were presented and counted aloud by the participant, there was a signal to recall aloud the separate sums associated with all of the screens that had been presented, in the presented order. There is the theoretical possibility that the contents of attention are recalled, after which the participant's focus of attention returns to the activated memory field again for a second cycle of retrieval, or for multiple cycles. [Google Scholar]Baddeley A, Gathercole S, Papagno C. If there is no such knowledge (for N-k items), then the subject still will answer correctly with a probability 1-g, where g is again the probability of guessing “yes.” For this revised theory, given that memory is used to respond in the no-change situation, it is useful to define performance in terms of the rate of correct rejections, CR. The outcome was a very clear crossover interaction of presentation rate and strategy. (2) The participant practiced recalling one 5-digit list and one 7-digit list immediately upon hearing it; there were no distracting stimuli. A controlled-attention view of working-memory capacity. They showed a superiority of digit span over other measures, as the older groups did. Unfortunately, as in most meta-analyses, different measures had to be drawn from different studies, making the comparability of the measures questionable.Haarman, Davelaar, and Usher (2003) developed a "conceptual span" task in which list recall was to be organized according to semantic elements (e.g., in an example they offer: "lamp, pear, tiger, apple, grape, elephant, horse, fax, phone," FRUIT? (p. Models of short-term memory. Perception & Psychophysics. The predictions tested in the present article pertain to the scope of attention, whereas the adjustable nature of the focus allows consistency with other highly relevant research (e.g., Kane, Bleckley, Conway, & Engle, 2001).We do not judge the success of this endeavor by whether storage-and-processing measures or the proposed alternative, scope-of-attention measures, pick up more variance in aptitude tasks. Models of working memory: Mechanisms of active maintenance and executive control. (2003), which focused on response timing. The creation, rather than elimination, of proactive interference is theoretically desirable because the attention-related, capacity-limited WM mechanism appears to provide some immunity to proactive interference for a few items (Cowan et al., in press; Halford, Maybery, & Bain, 1988) so that, under high-interference conditions, the contributions of capacity-limited WM are presumably maximized. We believe that participants must extract information from a visuospatial record into the focus of attention before the presentation of the second array (see Cowan, 2001). The listening and counting span tasks involved the same materials as in Experiment 2 but the order of trials was changed to be more like the digit span. Developmental changes in speech rate and memory span: A causal relationship? The highest of these correlations (e.g., between listening span and running span: r = .56; rp = .37) compare favorably with the correlations between listening span and counting span (r = .52; rp = .37). [PubMed] [Google Scholar]Cohen RL, Heath M. For visual-array comparisons, which involved recognition, the span was defined as the smallest set size at which at least 75% of the responses were correct (i.e., half-way between chance and perfect performance).A second method of scoring, maximal number correct, was available for all measures. Working memory and retrieval: A resource-dependent inhibition model. Standard Progressive Matrices Including the Parallel and Plus versions. 1995;23:181–191. 1992;16:81–97. It can account for the finding that the difficulty of the processing task within storage-and-processing tasks is not particularly critical (Duff & Logie, 2001), given that even a relatively easy task might interfere with rehearsal and grouping processes almost as much as a more difficult task, by tying up articulatory processes and central executive processes needed to initiate rehearsal and grouping (cf. The tasks were programmed in the SuperCard language (Solutions Etcetera, Pollock Pines, CA) with the exception of the counting- and listening-span tasks, which were run on a personal computer using MEL version 2.0 (Schneider, 1988). Is working memory capacity task dependent? The complexities of complex span: Explaining individual differences in working memory in children and adults. (1999) but other aspects of the procedure were the same. The revised estimation method will be used in data analyses.This method of scoring involved the longest list length of at least 50% correct for the digit, counting, and listening span; average number correct for running span and ignored speech; and the largest set size of at least 75% correct for visual-array comparisons. For example, it makes sense to speculate that an individual who can attend to four objects at once would be better prepared to understand a two-way interaction of factors than an individual who can attend to only two objects at once, but there appears to be no relevant evidence.The work on the scope of attention also may be related to the episodic buffer, a component of WM that recently has been proposed to serve the function of storage for combinations of elements that cannot be included in the phonological or visuospatial storage mechanisms (Baddeley, 2000, 2001). Like behavioral capacity, it increased up to a maximum of 3 to 4 items and then increased no more. [PubMed] [Google Scholar]Towse JN, Hitch GJ, Hutton U. Case et al. [Google Scholar]Pascual- Leone JA. However, the basic expectation is that most of the variance that is shared between listening span and counting span will be shared with scope-of-attention tasks, as well.Expectation 3: Measures of Aptitude and the Development of Rehearsal We expected that, in participants of all ages, tasks that make it difficult to apply attention to improve encoding and maintenance processes (i.e., both storage-and-processing tasks and scope-of-attention tasks) would yield lower estimates of capacity than a task that readily permits attentive encoding, rehearsal, and grouping (digit span). This finding reinforces the conclusion that sufficient sensory memory was available at short test delays so that performance limits were not due to sensory memory decay. The recent research literature on the link between attention and WM has focused primarily on the control of attention whereas, we suggest, a meaningful scale of WM capacity depends on an emphasis on the scope of attention.The control of attention was an important element of early theories of information processing (e.g., Atkinson & Shiffrin, 1968) and is embodied in the central executive component of theoretical conceptions of WM (e.g., Baddeley, 1986; Cowan, 1988, 1995). It included a sequence of task phases designed to train the participant, provide familiarization with the necessary stimuli, and assess the deployment of attention in the main phase of the task. The digits were recorded and presented at a normal rate, with each digit under 400 ms long. However, their criterion task was reading recognition and the children spanned the ages of 7 through 13 years, so the older children may differ from the younger ones in both reading and rehearsal skills. 2003;6:316–322. In contrast, in the conception of WM as a multi-component system (e.g., Baddeley, 1986; Baddeley & Logie, 1999), attention tended to be associated with executive control but not with storage per se; that storage was assumed to be automatic once the information was entered into it, and it was assumed to be time-limited instead of capacity-limited. Recall that memory for attended speech surpasses memory for ignored speech in young children (Figure 1).Our interpretation of the developmental pattern is that it has at least two components. Journal of Experimental Psychology: Learning, Memory, & Cognition. [PubMed] [Google Scholar]Naveh-Benjamin M, Jonides J. First, rehearsal might be present in some children and not others, producing more variability in digit spans in children than in adults. [Google Scholar]Mewhort DJK, Johns EE. 1999;27:759–767. This is especially effective if the number of items to be presented is unpredictable, so that each item cannot be classified as occupying a certain slot within a known list structure. This has been taken to indicate that what is most critical is the ability to retain information in memory even while carrying out processing, an ability that would seem to require the control of attention. Moreover, Stevanovski and Jolicoeur (2003) found considerable interference in a similar procedure with a simple tone-discrimination task between arrays. " That sentence is typical in difficulty level (e.g., "a chicken lays eggs"; "you wear pants on your arms") and no sentence was used more than once. Stanford-Binet Intelligence Scale: Fourth Edition. [Google Scholar]Tuholski SW, Engle RW, Baylis GC. Miller. (1999, 2000) found pronounced bow-shaped serial position functions in memory for ignored speech, so sensory memory for even the early serial positions seemed to remain available at the time of list-recall testing. (If the items were not sufficiently familiar, some items might be represented as multiple chunks; and if grouping and rehearsal were not prevented, multiple items might be grouped together to form a smaller number of chunks.) Grouping and at least the initiation of rehearsal presumably require attention (e.g., Guttentag, 1984; Naveh-Benjamin & Jonides, 1984) so, to limit grouping and rehearsal, attention must be diverted or thwarted.Various procedures appearing to meet that requirement led to convergent estimates of about 4 items (i.e., chunks) recalled in adults, and fewer in children (Cowan, 2001; Cowan, Elliott, & Saults, 2002). Storage-and-processing tasks correlate with aptitudes, according to this view, largely because the processing task prevents rehearsal and grouping of items to be recalled. The effects of word length and phone mic similarity in young children's short-term memory. What is unique about this study is the incorporation of measures designed or selected according to the theoretical view that it is possible to measure how many chunks of information can be held in the focus of attention at one time (Cowan, 2001). Thus, the formula for the hit rate H is (This formula was misreported by Pashler due to a moved bracket, but the intent was clear from the text.) The false alarm rate FA (incorrectly guessing “yes” when there was no change) was taken as an estimate of g: Substituting FA for g in Equation 1 and rearranging terms, it can be calculated that $k = N*(H - FA)/(1 - FA)$(3) Although this equation gives a rough estimate of memory capacity, it makes the assumption that WM is not used to improve performance in the no-change situation. Fit indices: GFI = goodness-of-fit index, AGFI = adjusted goodness-of-fit index, TLI = Tucker-Lewis index, CFI = comparative fit index, RMSEA = root mean square error of approximation.Last, Table 10 illustrates the success of the theoretical expectation that digit span would be much more predictive of the within-age portion of g in children too young to rehearse efficiently than in older participants. 1988;14:278–288. Nature. This model groups together all of the measures of the scope of attention and the storage-and-processing tasks, as both types are said to provide an index to an attentional resource labeled the capacity of attention. However, we already know that children too young to rehearse still receive a considerable advantage from attending to a digit list as opposed to ignoring it (see Figure 1). Recall from a long-term memory record includes much more than the 4-chunk limit, though they appear in bursts of about 4. Five seconds or sixty? [PubMed] [Google Scholar]Ericsson KA, Kintsch W. (2004). pp. However, in pilot data, we learned that a higher list length was helpful in discriminating among adults, though it was discouraging to many children. Resource reciprocity: An event-related brain potentials analysis. 89–195. NY: Henry Holt; 1890. Delayed recall and the serial-position effect of short-term memory. Maintenance rehearsal: A two-component analysis. Perhaps the first such procedure was carried out by Jevons (1871), who picked up a small handful of beans and threw them on the table to be enumerated as quickly as possible. Chen, 2003; Usher et al., 2001) is a function of the ability to control attention. Attentional focus, processing load, and Stroop interference. The resulting stimuli sounded clear and natural but a bit rapid, as in certain advertisements in which compressed speech is used. These digits were delivered by computer and played over headphones at 66–68 dB (A). The last spoken list ended 1 or 5 s before the recall probe appeared. (2004).Further analyses served to investigate the nature of the variance, in prediction of aptitudes, that was not shared between the storage-and-processing and the scope-of-attention measures, but was unique to one of them. These analyses were not intended to be complete but to investigate relatively large portions of the variance. However, the stimuli were series of sine wave tones, each 200-ms-long tones (constructed with 11-ms, linear onset and offset ramps). For symmetry with Variant 1, the test began with seven response boxes, then six, and then five, with nine test trials per list length. The activated memory record could fade before more information is drawn into the focus of attention. Morey, University of Missouri - Columbia.Sam Mattox, University of Missouri - Columbia.Anna Hismjatullina, University of Missouri - Columbia.Andrew R.A. Conway, University of Illinois - Chicago.Anderson JR, Lebière C. The information available in brief visual presentations. At the fastest rate across 10 serial positions, there was about a 0.3-to 0.4-item advantage for a passive strategy over an active strategy. A different result obtained for auditory arrays, for which the capacity was actually lower using changes to a unique tone (M = 4.03, SEM = 0.15) than to a non-unique tone (M = 4.32, SEM = 0.16), F(3, 123) = 9.10, MSE = 0.58, p < .01. A WM span score would not indicate which type of person had been tested.Moreover, there is a fundamental difficulty in interpreting the results of dual tasks (of which, storage-and-processing tasks are one type). The largest portions of variance were the one shared between measures (.09) and the one unique to the scope-of-attention measures (.09).Experiment 1, prediction of high school grades percentile in adults, conjointly by subsets of three types of WM variable. [PubMed] [Google Scholar]Saito S, Miyake A. The main point of the study was to use partial-report cues to determine how much information persisted in sensory memory but, without a partial-report cue to enable attention at encoding, only about 4 items could be recalled.Although the scope of attention presumably limits how many chunks of information can be extracted from the activated memory field, or apprehended, at once, there is another important limit that must be considered. One might speculate from this finding that a general scope of attention (as one presumably examines in visual-array comparisons) is not an important source of individual differences in WM, which therefore might be attributed instead to the control of attention in the retention of auditory and phonological sequences. We started with small arrays and kept increasing the set size until the participant fell below 75% correct performance for a set size. Oxford Psychology Series #11. Vogel and Machizawa (2004) provided a cue to attend to colored squares on one side of the screen while ignoring those on the other side and used the extra event-related electrical activity on the side of the scalp contralateral to the attended field as an index of WM maintenance. British Journal of Educational Psychology. [Google Scholar]LaBerge D, Brown V. That is to be expected if the shared predictive variance reflects the scope of attention.An exception to the success of the scope-of-attention measures is that visual-array comparisons did not correlate with practical measures of aptitude in adults (ACT scores or high school grades Experiment 1). Morey and Cowan (2004) replicated that effect using 2-digit loads repeatedly spoken aloud, and also found no effect of overt, repeated recitation of the participant's own 7-digit telephone number during the visual-arrays task. A second component is a developmental increase in the ability to use covert verbal rehearsal and grouping, improving the way in which digit span is carried out. This difficulty stems largely from the reliance on dual tasks in the measurement of WM capacity (which include separate storage and processing task components). Unlike Morey and Cowan (2004), Cocchini et al. Cocchini et al. 2003;29:3–18. [PubMed] [Google Scholar]Thorndike RL, Hagen EP, Sattler JM. However, the interaction of Age×Condition did not reach significance and was in the unexpected direction, with slightly larger differences in older participants.Table 2 shows the raw correlations between measures (below the diagonal), reliabilities of the measures calculated as Chronbach's Alpha across trial subsets (in bold, on the diagonal), and correlations with age group variance partialled out (above the diagonal). 1982;33:386–404. Third Edition. Attention also is needed to initiate a rehearsal loop that preserves the information in a passive store, even if the rehearsal loop then proceeds automatically (cf. Oberauer, 2002). Overall, summing the portions of each circle, the proportion of ACT variance accounted for was .26 for storage-and-processing measures, .18 for scope-of-attention measures, and .11 for digit span; the lower value for digit span was to be expected given that rehearsal may obscure the use of attention in this task. The gradient can be set narrowly or widely, and it does not matter to us whether a zoom description or a gradient-setting description is used.As will be discussed, attention cannot be spread infinitely thinly but is limited to about 3 to 5 chunks of information (Cowan, 2001). First, Table 1 and Table 6 show considerable variation in the means of different scope-of-attention measures. This was to provide familiarity with the spoken lists and their lengths. It turned out that these portions of the predictive variance primarily reflected skills specific to one task. An additional 9 second-graders, 8 fourth-graders, 7 sixth-graders, and 3 adults provided only partial data and were omitted from the final sample.All programming was accomplished using the Supercard program. If this happened, then the memory response would have to be taken as an overestimate of the scope of attention. Also to make time, given the high reliability of the digit-span test, we carried out only a single run of digit span rather than the two runs carried out in Experiment 1. Current Directions in Psychological Science. A neoPiagetian view of developmental intelligence. Constant capacity in an immediate serial-recall task: A logical sequel to Miller (1956) Psychological Science. [PubMed] [Google Scholar]Kahneman D, Treisman A, Gibbs BJ. Age group based on year in school was used as a developmental variable in the correlations rather than age in months because of evidence that it is a stronger predictor of scholastic skills (Bentin, Hammer, & Cahan, 1991; Cahan & Cohen, 1989). As in Experiment 1, this difference cannot be attributed to wider variation in scores (or in relevant abilities such as rehearsal) among the younger children. 1972;3:255–267. [PubMed] [Google Scholar]Gathercole SE, Baddeley AD. (There was a difference at the final serial position but it was not enough to result in a significant age difference in list-wide decay.) In sum, there appears to be a constant capacity for digits within ignored lists; the capacity appears to be related to the scope of attention when it is focused on the sensory memory record of the list, as opposed to sensory memory decay; and this capacity changes with development during childhood.Running memory span In running memory span (Pollack et al., 1959), participants receive many verbal items in a list that ends at an unpredictable point, whereupon the items at the end of the list are to be recalled. As expected, adding digit spans to the model made it no longer fit (chi-square = 55.75 with df = 32, p < .01). The processing-speed theory of adult age differences in cognition. Journal of Memory and Language. (3) The participant saw 14 sets of 5 pictures and simultaneously heard their names; with the members of each set all rhymed with one another (e.g., box, rocks, clocks, socks, fox). When the 75% criterion was not met, a final set of 12 trials was conducted at the largest set size at which it had been met.The auditory-sequences task was analogous to the visual-arrays task. The search for what is fundamental in the development of working memory. However, at least two types of findings argue against a limitation in the persistence of activated features as the source of the memory limit in procedures reviewed by Cowan (2001): constant capacity across different decay conditions, and insensitivity to stimulus-array duration. 2001;29:774–776. This could be the case, for example, if attention can be adjusted. 1978;4:86–100. An additional 7 third-graders, 7 fifth-graders, and 4 adults provided only partial data and were eliminated from the sample. third edition. He presented lists of spoken or printed digits at a rate of 900 ms/digit in a running span procedure. The cocktail party phenomenon revisited: The importance of working memory capacity. To the extent that certain other skills are needed in the aptitude test, there should be a unique relation between counting span and that aptitude. In: Kail R, Reese H, editors. How are visuospatial working memory, executive functioning, and spatial abilities related? 2002;28:411–421. A similar finding was obtained when individuals were compared at absolute list lengths, as opposed to lengths determined relative to span (not shown).At least two points must be established before it can be inferred that these solid lines reflect the scope of attention at the time that the recall cue is presented: first, that the limit in the recall of ignored information is not a result of residual attention to the list during its presentation and, second, that the limit is not a result of a sensory memory deficit. 1990;16:258–269. Psychological Science. Correct answer: apple, pear, grape"). However, there is evidence that pattern matching plays an important role in subitizing (e.g., Logan & Zbrodoff, 2003), so that it may not be a direct measure of the scope of attention as Cowan (2001) had supposed (although see Basak & Verhaeghen, 2003). 2003;132:47–70. Stanford, CA: Stanford University Press; 1989. [Google Scholar]Conway RA, Cowan N, Bunting MF. Theory of attentional operations in shape identifications. In one method (traditional span), for tasks that involved list recall with increasing list lengths, the participant's span was defined in the traditional manner, as the lowest list length at which at least 50% of the lists were recalled correctly. 1968;76:618–622. Distinguishing short-term memory from working memory. The main issue is whether measures of WM designed to examine the scope of attention perform in a manner comparable to measures that involve storage and processing together, even though the scope-of-attention measures do not impose a simultaneous dual task. [PubMed] [Google Scholar]Fry AF, Hale S. 1966;37:283–299. In running span, the answer display always showed 6 slots and the Version 2 instructions of Experiment 1 were used. The effect was highly significant in each age group and planned comparisons indicated that, within each age group, the digit-span mean was significantly higher than the mean for each of the other five WM measures, p < .01, with one exception. (5) Differences between high-and low-span individuals (measured by storage-and-processing WM tasks) have been obtained even in tasks in which the only apparent storage requirement is to hold onto the goal of the task. 1991;43A:35–52. [PubMed] [Google Scholar]Broadbent DE. [Google Scholar]Gathercole SE, Pickering SJ. Access to information in working memory: exploring the focus of attention. The capacity was only marginally higher using changes to a unique color (M = 5.11, SEM = 0.17) than using changes to a non-unique color (M = 4.95, SEM = 0.14), F (3, 123) = 3.81, MSE = 0.39, p < .06. 1985;3:175–181. [PubMed] [Google Scholar]Mayes JT. Working memory, intelligence and learning disabilities. The table shows that, although digit span was about as predictive as other types of WM measures of within-age-group variance in the younger subsample, it was of no predictive value for within-age-group variance in the older subsample. This change was made to save running time, given the extremely high reliability of digit span obtained in Experiment 2. [Google Scholar]Jolicoeur P. The outcome of those regressions (not shown) was very similar to those presented here, which have the advantage that they can be further decomposed, as will be seen.Experiment 1, Increases in R2 for WM Measures in Stepwise Regressions Predicting Different Scholastic IndicesRegressionCollege StudentsChildrenStepPredictorsACTH.S. GradesCAT1Storage & Processing.26**.13*.14**2Digit Span.00.00.17**3Scope of Attention.02*.14*.062Scope of Attention.02.09.16**3Digit Span.00.05.06*1Scope of Attention.18*.18*.24**2Storage & Processing.10*.04.063Digit Span.00.05.06*2Digit Span.00.04.09**3Storage & Processing.10*.04.041Digit Span.11*.02.27**2Storage & Processing.15**.11.043Scope of Attention.02*.14*.062Scope of Attention.07.20**.063Storage & Processing.10*.04.04Figure 3 shows the resulting diagram of variance in the prediction of ACT scores (adults). 1986;40:225–240. The multiple faces of working memory: Storage, processing, supervision, and coordination. 1988;44:369–378. However, within that framework, it has long been thought that some individuals require more of that common resource than others to accomplish a given task because expertise leads to efficient use of the resource (e.g., Case et al., 1982). All WM measures were correlated with the most generally accepted measure of fluid intelligence, Ravens Progressive Matrices. The premise behind this task appears to be that it is a way to measure attentional capacity; attending to information may be tantamount to selecting objects by categorizing them (see Logan, 2002). One possibility is that the scope of attention does not meaningfully vary between normal individuals within an age group but that the process of zooming in to hold onto a goal and zooming out to apprehend a maximal field of objects (cf. On each trial, an array of solid-colored squares on a gray screen was followed by a second array that was identical to the first or differed in the color of one square. Listening span was presented in a female voice, whereas all spoken digits were presented in a male voice.This was a computerized version of the usual psychometric digit-span test, but with more trials per list length to increase the reliability. It presumably could not be verbal rehearsal because a great deal of research on articulatory suppression (see Baddeley, 1986) indicates that recitation of the verbal digit load should prevent the application of verbal rehearsal to the visual arrays. 29. However, when there is no interference with the goal and the task has been well-practiced, the focus of attention could afford to zoom out to apprehend multiple items at once, up to its limit. This might take the form of individual differences in the passive storage of information, as in the phonological loop (Gathercole & Baddeley, 1993), or individual differences in how many unassociated units or chunks can be held in the focus of attention (Cowan, 2001). 2002;31:167–193. [Google Scholar]Hedden T, Park DC. Processing speed, working memory, and fluid intelligence: Evidence for a developmental cascade. This recall probe comprised a series of boxes, one for each digit in the last spoken list, that were to be filled in with digits. The expectation was that these outcomes would be obtained not only in raw correlations across age groups, but also in correlations with age-group variance removed.Expectation 2: Task-Specific Additional Variance We expected that additional variance on specific aptitude tests will be picked up by particular WM tasks based on what skills the two have in common. [Google Scholar]Swanson HL. These means produced correlations that were generally slightly higher than those obtained for the first scoring method. Yet, for that interpretation, it is puzzling that the storage-and-processing tasks and digit span are roughly comparable in variability, as Table 1 shows. The present study addresses these unknowns. The apprehension of these items would allow a change to be detected if one of these k items should happen to be the changed item. 2000;71:981–1003. In Experiment 2, in which both types of measures were obtained more uniformly, with incremental set sizes in a span-type procedure (except running span), the results were similar. The role of prefrontal cortex in working-memory capacity, executive attention, and general fluid intelligence: An individual-differences perspective. Given that this was the only measure of WM for visual arrays as opposed to verbal or auditory sequences, it suggests that the practical measures of aptitude were heavily influenced by auditory and verbal skills. Phonological similarity in working memory. Overall, storage-and-processing tasks accounted for .14 of the variance, scope-of-attention tasks accounted for .24, and digit span accounted for .27. During reception and maintenance, it might be used to recode the items so as to convert them to a smaller number of separate chunks of information. Measures: RS = running span, VA = visual arrays, AS = auditory sequences, CS = counting span, LS = listening span, RA = Ravens Progressive Matrices, PA = Stanford-Binet pattern analysis, VO = Stanford-Binet vocabulary, PV = Peabody Picture Vocabulary Test, NVIQ = nonverbal IQ, VIQ = verbal IQ. To make time for it and for the psychometric tests, we dropped the very time-consuming, ignored-speech task from the test battery. 2002;30:163–183. 1999;70:1082–1097. Clearly, the two types of measures shared considerable variance in the prediction of aptitudes, and were relatively similar in their predictive abilities. The finding in all of these studies was that there is a memory record of the ignored speech channel but that, in comparison to memory for attended speech, successful memory for ignored speech requires a shorter retention interval between presentation and test (≤2 s for maximum

performance). However, Broadbent's (1958) conception of a limited-capacity storage faculty seemed to view it as being the direct consequence of attention, given that an attention filter stood between a large-capacity store of information coming directly from the senses and a small-capacity store of information coming after that information was filtered. Auditory sequences, which were introduced only in Experiment 2, were scored in the same way as the visual arrays, using the capacity formula explained in Appendix A.Table 6 shows the means and age effects in this experiment. The second array remained on the screen until the response was made. 2003;10:676–682. 1999;22:77–126. For example, whereas Sperling (1960) found that the benefit of a partial-report cue (which allows sensory memory to be used efficiently) was effective only up to a fraction of a second, Darwin, Turvey, and Crowder (1972) carried out a similar procedure with a spatio-temporal array of spoken digits and found that a partial report cue was effective up to about 4 s. (2003) suggest that domain-specific storage and cross-domain processing work separately, not from a common resource. Scope-of-attention measures do not provide the highest correlations with the aptitude measures; overall, storage-and-processing measures do. In a developmental study, we document that several scope-of-attention measures that do not include a separate processing component, but nevertheless prevent efficient rehearsal or grouping, also correlate well with aptitudes and with storage-and-processing measures. [Google Scholar]Jahnke JC. 1994;123:354–373. Kahneman, Treisman, & Gibbs, 1992). For example, if a participant's mean number correct was 2.6 for 3-word lists, 3.2 for 4-word lists, and 3.0 for 5-word lists, span would be defined as 3.2. For the visual-array task, the number-correct calculation at each set size was based on a simple model of performance that corrects for guessing, as explained in Appendix A.Means and age effects, correlations, and regressions are discussed in turn with respect to the hypotheses under investigation.The means for WM measures yielded quite similar results for the two methods of scoring described above. [Google Scholar]Flavell JH, Beach DH, Chinsky JM. [PubMed] [Google Scholar]Turner ML, Engle RW. Working memory. It can do the latter in several ways. Behavioral & Brain Sciences. Between 5 and 10 lists were presented, separated by 1- or 5-s silent intervals that were randomly ordered, before the recall probe was presented. If the items are familiar to begin with then the hope is that, at the time of recall, each item that is recalled was retrieved from the passive trace into the focus of attention as a single, separate chunk formed in the focus of attention. [PubMed] [Google Scholar]Eriksen CW, St. James JD. The answer is 62% (for the ACT), 69% (for high school grades), 57% (for the CAT), 73% (for the g factor), and 50% (for the within-age-group portion of g). The first experiment concentrated on WM tasks that have been tested before (although never in the same study) and a set of applied measures of scholastic ability. Presentation time in expert memory. One can find the unique contribution of A by finding the R2 value for a regression that includes A, B, and C and subtracting from it the R2 value for a regression that includes just B and C; the contribution shared between A and B can be determined by adding the R2 values for A and B when entered singly and subtracting from that sum the R2 value for A and B entered together; and so on, until all combinations are determined.Table 5 shows sets of regressions carried out in the prediction of three criterion variables: ACT composite scores, high school grades, and (for children) CAT composite scores. [PubMed] [Google Scholar]Kane MJ, Hambrick DZ, Tuholski SW, Wilhelm O, Payne TW, Engle RW. Participants were given multiple opportunities for breaks throughout both sessions. Automatic and controlled processing in sentence recall: The role of long-term and working memory. There are several arguments against this, and in favor of the suggestion that the focus of attention can consult activated memory only once. 1969;21:85–93. In the older groups, we propose, rehearsal allows items to be grouped and memorized and the ability to use strategic processing in this way is separate from the scope of attention. Specifically, we expected (a) that these two types of tasks should correlate well, and (b) that the scope-of-attention procedures should capture general variance in aptitudes just about as well as storage-and-processing procedures. [PubMed] [Google Scholar]Penney CG. According to an alternative proposal, though, participants wait passively until the list ends and then retrieve items from the automatically activated memory stream (e.g., from sensory memory).Two studies greatly strengthen the latter interpretation when the items are presented quickly. Individual differences in working memory capacity predict visual attention allocation. For example, consider the finding of non-frontal loci for capacity limits in a visual-array comparison task (Todd et al., 2004) along with documented individual differences in event-related signals related to capacity in that task (Vogel & Machizawa, 2004), in contrast to pronounced prefrontal loci for the control of attention (e.g., Kane & Engle, 2002). In: Atkinson RC, Herrnstein RJ, Lindzey G, Luce RD, editors. James (1890) discussed primary memory as the trailing edge of consciousness, thoroughly related to the concept of attention. No cue was presented to mark the tone that might have changed; although at most one tone changed between the two series on a trial, the task was to compare the entire first and second series and determine whether they were the same or different.The psychometric tests were conducted in the age-appropriate manner stated in each of the test manuals. We will discuss each of these assumptions in turn, and then show how they apply to tasks that will be used in the present study.Multiple uses of attention in memory tasks Attention is potentially involved in the reception, maintenance, and retrieval of information. These digits could be typed into the boxes starting with the first box and ending with the last digit remembered or guessed. [PubMed] [Google Scholar]Caplan D, Waters GS. In Experiment 2, therefore, we altered the method of the visual array and auditory sequence tasks to be more like the other tasks. In running memory span, no set-size manipulation was possible, give n that the hallmark of the procedure is unpredictable list length. For fifth-grade children, the corresponding means were 5.49 (0.17), 3.54 (0.17), 2.65 (0.18), 2.42 (0.12), 1.60 (0.12), and 6.03 (0.41) and, for adults, they were 7.35 (0.14), 3.97 (0.11), 3.86 (0.12), 3.39 (0.09), 2.31 (0.12), and 8.22 (0.26). An auditory analogue of the Sperling partial report procedure: Evidence for brief auditory storage. [Google Scholar]Conway ARA, Engle RW. The present theoretical suggestion is that a single retrieval process occurs when retrieval is from an activated memory field, whereas multiple retrievals can occur when retrieval is from long-term memory, though both share the same capacity limit for each retrieval.Analyses of Specific Scope-of-Attention Tasks We argue that three tasks that will be used in Experiment 1 appear to conform to the requirements of good measures of the scope of attention. Models of Working Memory: Mechanisms of active maintenance and executive control. We therefore omitted the digit-span measure, which contributed nothing uniquely, and the resulting diagram is shown in Figure 4. These results are in keeping with the expectation that digit span produces higher performance than the other measures. [Google Scholar]Näätänen R. The means for all measures are strikingly similar to those of Experiment 1. The factor loadings were, for the PPVT, .90; for the Stanford-Binet Vocabulary test, .84; for the Ravens, .77; and for Stanford-Binet Pattern Analysis, .73. The phonological loop as a language learning device. Rather, success will be judged by whether the variance that is picked up contributes to our understanding of the processes underlying the generally-observed relation between WM and intelligence. New York: Pergamon Press; 1958. However, that is not the case. (2) An alternative account of the correlations based entirely on knowledge can be ruled out. Both of these expectations were fairly well-met and will be considered in turn.Correlations Between Storage-and-Processing Tasks and Scope-of-Attention Tasks In Experiment 1, all six correlations between the two storage-and-processing tasks and the three scope-of-attention tasks were significant, even with age group partialled out (Table 2). 2001;130:199–207. 739–811. [Google Scholar]Pascual- Leone J. On each trial, a list of digits (selected from the set 1 – 9 randomly without replacement) was presented by computer through headphones at 68–70 dB(A), at a rate of one digit per second. [Google Scholar]Morey CC, Cowan N. An advantage for spoken digits over printed digits was obtained at each of the last 7 serial positions, which suggests the presence of an auditory-modality-specific memory code at these positions (for discussion of modality effects see Nairne, 1990; Penney, 1989).Second, Hockey (1973) gave participants instructions to process the running-span stimuli either in a passive manner (a request that was further elaborated), or in an active manner, with instructions to "Concentrate on the items as they arrive, trying to form them into groups of three" using a rhythmic type of rehearsal. The time spent on retrieval is time unavailable to initiate and execute rehearsal and grouping.Prediction of Scholastic and Intellectual Aptitudes Figure 3 – Figure 5 (in Experiment 1) and Figure 7 – Figure 8 (in Experiment 2) summarize well the relation between storage-and-processing tasks and scope-of-attention tasks in terms of their joint and unique prediction of aptitudes. Session 1 included (1) running memory span, (2) counting span, (3) listening span, and (4) visual array memory. All participants reported normal or corrected-to-normal vision (including color vision) and normal hearing. Given that serial order recall is required, the relative serial positions of the items in the retained set would have to be continually updated, also. For simplicity, the criterion measure that was used was a g factor based on a factor analysis of the four aptitude scores (principal axis factoring), which yielded only a single factor that accounted for 66% of the total variance in these scores (Eigenvalue = 2.66). Indeed, the dependent measure of the ability to maintain a goal differs widely from one test situation to the next (cf. 2003;48:320–345. For evidence that there is considerable generality of WM and its importance for aptitudes across domains despite the additional influence of domain-specific skills, see Kane et al. Although attention has not been diverted from the stimuli, it is ineffective at producing grouping or rehearsal. 2001;24:152–153. Do young children rehearse? (1982) similarly combined counting of displays of objects and recall of the sums (counting span), and Turner and Engle (1989) combined arithmetic with word recall (operation span). A more realistic assumption for our task is that there would be no guesswork for k items in the unchanged array. In Span Run 1 there were four 2-digit lists as practice and then test trials beginning at that same list length. [PubMed] [Google Scholar]Basak C, Verhaeghen P. So does digit span in children too young to rehearse.Keywords: working memory, short-term memory, individual differences, variation in working memory, cholastic abilities, intellectual abilities, attention, capacity, storage capacityBaddeley and Hitch (1974) highlighted a key theoretical construct, working memory (WM), which can be described generally as the set of mechanisms capable of retaining a small amount of information in an active state for use in ongoing cognitive tasks (though it now means different things to different investigators; see Miyake & Shah, 1999). [PubMed] [Google Scholar]Logie RH, Gilhooly KJ. Pashler's formula assumed that, upon examining a briefly presented array of N items, the subject is able to apprehend a certain fixed number of items, k. [PubMed] [Google Scholar]Oberauer K, Süß H-M, Wilhelm O, Wittmann WW. Memory & Cognition. [Google Scholar]Gray JR, Chabris CF, Braver TS. Span was defined as the mean number correct at whatever list length or set size this mean number correct was maximal. An important approach to WM has blossomed, in which experimental and psychometric methods are synthesized (e.g., Conway, Cowan, Bunting, Therriault, & Minkoff, 2002; Cowan et al., 1998; Engle, Tuholski, Laughlin, & Conway, 1999; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001).Research on WM suggests that the measures used most often to examine individual differences have both strengths and weaknesses. It may be that the people who are good at locking attention onto a goal during adversity are the same ones who are good at zooming attention out to apprehend the maximal number of items, or who have the widest attentional focus. Those who did (N = 127) included 29 second-grade children (12 male, 17 female; mean age = 99.52 months, ranging from 85 to 108 months, SD=4.97), 36 fourth-grade children (17 male, 19 female; mean age = 121.22 months, ranging from 103 to 133 months, SD=7.54), 33 sixth-grade children (20 male, 13 female; mean age = 143.00 months, ranging from 133 to 152 months, SD=5.81), and 29 adults (14 male, 15 female; mean age = 227.38 months, ranging from 217 to 255 months, SD=9.93). Does performance on memory for order correlate with performance on standardized measures of ability? 2002;45:153–219. Examiner's manual for the PPVT-III Peabody Picture Vocabulary Test. First, cross-age variance provides a wider range of variability in task performance than one finds among adults (a research priority advocated, for example, by Pascual-Leone, in press). (6) Recent research has suggested that the functioning of frontal-lobe areas related to executive control of attention differ between high-and low-span individuals (as measured by storage-and-processing WM tasks). 1988;104:163–191. New York: Wiley; 2002. The magic number and the episodic buffer. 2004;51:623–643. 1999;6:87–92. Advances in Child Development and Behavior. Cowan (1988, 1995, 1999) advocated both attention-free and attention-dependent forms of storage, with only the attention-dependent forms limited in capacity per se.Broadbent (1975) suggested that there is a form of storage that is limited to 3 items. Cowan (2001) conceived of this measure as the result of a limited-capacity attentional focus extracting chunks of information from a field of activated features in memory in order to allow an explicit memory response. Two of the measures yielding relatively high correlations with the ACT (digit span, r = .37; listening span, r = .50) were not significantly correlated with high school grades (digit span, r = .15, n.s.; listening span, r = .26, n.s.). The reviewing of object files: Object-specific integration of information. Looking at the total variance in aptitude predicted by each kind of measure, in Experiment 1, the advantage in prediction of the ACT was for the storage-and-processing measures (.26 of the variance) as opposed to the scope-of-attention measures (.18). [Google Scholar]Tipper SP, Driver J, Weaver B. 2000;76:151–172. It can be seen that the measures were fairly reliable and all of the correlations were significant. Clearly, the differences that exist suggest either that the measures are not completely pure or that individuals can hold a different number of chunks in different processing domains. The magic number seven after fifteen years. [PubMed] [Google Scholar]Tombu M, Jolicoeur P. There are several relevant findings. Transient phonemic codes and immunity to proactive interference. 391–418. Eight practice trials were followed by 128 test trials, including an equal number of trials with 4, 6, 8, or 10 squares per array, with set sizes randomly ordered across trials. London: Sage; (in press) [Google Scholar]Tehan G, Humphreys MS. [Google Scholar]Duff SC, Logie RH. An unnecessarily zoomed-in focus when there is relatively little interference to be handled would decrease the apparent scope of an individual's attention in the task. 1991;43(A):289–298. (The sum of .10 exceeded the obtained .09 due to rounding error.) However, the sum of these skill-specific variance components in this case did not reach statistical significance.Figure 5 shows the distribution of variance for CAT composite scores in children. [PubMed] [Google Scholar]Miller GA. The capacity of visual working memory for features and conjunctions. No response was required for most such lists but, once a minute or so, the rhyming game was replaced by a digit-recall response screen shortly after the onset of the most recent list. We relied on the mean number of items correct within a list or set (for lists, the number of items recalled in the correct serial positions). 1989;28:127–154. Also, much of the advantage for the storage-and-processing measures was found in the age effects. When the digit list ended, it was replaced (270 – 280 ms after the last digit's onset) with a series of five, six, or seven response boxes to be filled in from left to right with digits, using the computer's number key pad.There were two variants of the running-memory task for the older children and adults. Recent advances in learning and motivation. Ruchkin, Grafman, Cameron, and Berndt (2003) summarized physiological evidence leading to the idea that the frontal region does not contain the information in WM directly but contains pointers to that information in more posterior regions of the cortex, potentially reinforcing the notion of a difference between a frontal control mechanism and a posterior seat of attention.It is an open question whether the integrity of the frontal and parietal portions of the attentional system are distinct or whether they function as an integrated system, such that their levels of functioning are strongly correlated among normal individuals. The stimuli were the same as in Experiment 1 except for the addition of the auditory-sequence comparison procedure. There is some evidence that participants do not always engage in attention-sharing between processing and memory maintenance, as one might assume; in some tasks, they appear to switch attention between storage and processing, provided that the processing task included rich semantic cues for retrieval of the memoranda (Copeland & Radvansky, 2001; Cowan et al., 2003; Hitch et al., 2001). Some studies have shown little or no dual-task interference (e.g., Cocchini, Logie, Della Sala, MacPherson, and Baddeley, 2002; Duff & Logie, 2001; Farmer, Berman, & Fletcher, 1986) but that proves only that not all tasks require a substantial amount of a general resource such as attention. Age versus schooling effects on intelligence development. Notice that all measures were intercorrelated. In each case, age was first partialled out. Working memory deficits in children with low achievements in the national curriculum at 7 years of age. Attention and performance. Annual Review of Psychology. We will offer a theoretical framework for doing so, and for measuring WM in a more meaningful way than is found with current measurement practices. 2002;30:1086–1095. 2000;4:417–423. In Variant 1, the instructions were to wait until the list ended and then try to recall (or guess) the last five, six, or seven digits from the end of the list (but in forward order), depending on the number of response boxes presented. 1985;2:211–228. However, in the literature on dual-task measures of WM, including the storage-and-processing tasks, there has been very little effort to use task combinations in which the storage and processing tasks share neither their sensory modality nor the types of coding that they most naturally elicit, so the basis of interference between storage and processing is usually unclear and probably complex.Making matters worse, the types of domain-specific coding that traditionally have been associated with WM (Baddeley, 1986) may be differentially related to a general resource. However, there are reasons to question this speculation. It is possible that there is a small contribution of the difficulty of combining two tasks, reflected in that shared component. The phases of the experiment and their purposes were as follows. Verbal memory span in children: Speech timing clues to the mechanisms underlying age and word length effects. In the younger two groups combined, the digit span SD = 0.77 whereas, in the older two groups combined, SD = 1.12.Experiment 2, Proportions of Within-Age Variance in g, By Types of WM Measure in Younger and Older ParticipantsMeasuresGrades 2 & 4Grade 6 & Adult(n = 65)(n = 62)Storage and Processing0.15*0.15*Scope of Attention0.14*0.11*Digit Span0.14*0.01All WM Measures0.24*0.17*This experiment provides a comparison of three different types of WM measures in the prediction of verbal and nonverbal aptitudes. 2001;130:224–237. 1999;128:309–331. Critically, if familiar items are presented and conditions at encoding and maintenance prevent grouping and rehearsal, then each item constitutes a separate chunk that can be retrieved into the focus of attention. Research by Wheeler and Treisman (2002) confirms that the need to retain the binding between two different features increases difficulty in this sort of task. These measures could be examined across all age groups.We also changed the WM measures somewhat to address questions emerging from Experiment 1. The revised method yields capacity estimates that are more constant across set sizes and less variable than those produced by Pashler's estimate. 1984;37:92–106. It was emphasized that only a small effect of load was obtained. Oxford Psychology Series, No. 26. 1994;22:201–207. Journa l of Experimental Psychology: General. Deconfounding serial recall. Children were recruited from the Columbia Public Schools system and received either $5 and a book for their participation, or $10. [PubMed] [Google Scholar]Cowan N, Elliott EM, Saults JS. The magical number seven, and or minus two: Some limits on our capacity for processing information. There are several ways in which the effects of attention during stimulus encoding and maintenance can be minimized (cf. We were unable to use the Venn diagram method because two negative areas were obtained. [PubMed] [Google Scholar]Conway ARA, Cowan N, Bunting MF, Therriault DJ, Minkoff SRB. [PubMed] [Google Scholar]Logan GD, Zbrodoff NJ. [PubMed] [Google Scholar]Swanson HL. Numbers within the overlapping sections of the circles do not represent collinarity between the variables, but portions of g variance that are predicted in common by the WM variables shown as overlapping.Experiment 2, prediction of within-age-group variance in g score (with age-group variance removed) based on four aptitude tests (Peabody Picture Vocabulary Test, Stanford-Binet Vocabulary subtest, Ravens Progressive Matrices, and Stanford-Binet Pattern Analysis subtest), conjointly by subsets of three types of WM variable. They correlate well with various mental aptitudes in adults, at a considerably higher level than do simple memory-span tasks, in which a list of items is simply presented for recall on each trial (for a meta-analysis see Daneman & Merikle, 1996). Although this distinction is not clean and absolute, frontal lobe damage often results in dysfunctions of the central executive control of attention, whereas parietal lobe damage more often results in dysfunctions of consciousness, such as unilateral neglect and anosognosia (in which an individual shows no sign of awareness of an ostensibly obvious disability, such as paralysis of a limb). Perception and the conditioned reflex. In fourth-grade children, the digit span and visual-array comparison means did not differ significantly.As in Experiment 1, we examined capacity estimates from the visual-array comparison procedure based on just those trials in which the changes were to a color that was or was not already present in the array. Although performance on visual-array comparisons was at the expected level using the 75% correct span measure, it was an item or so higher with the maximal measure. In: Gathercole S, editor. 1989;17:398–422. American Guidance Service; 1997. 2001;8:331–335. Effects of domain knowledge, working memory capacity, and age on cognitive performance: An investigation of the knowledge- is-power hypothesis. Individuals who excel at controlling attention could be the same ones who have the largest scope of attention. [Google Scholar]Bleckley MK, Durso FT, Crutchfield JM, Engle RW, Khanna MM. In successive 5-year periods between 1980 and 2000, the numbers of entrees were 16, 21, 60, and 113. London: Sage; (in press) [Google Scholar]Pashler H. Other studies have suggested that what is critical is the amount of proactive interference that is already present by the time that long list lengths are used, and individual or age differences in the ability to overcome that interference by inhibiting it (Conway & Engle, 1994; Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999). One square in the second array was encircled (from the onset of that array) and, if the arrays differed at all, it was in the color of the encircled square. [PubMed] [Google Scholar]Logie RH, Della Sala S, Wynn V. It is difficult to explain this effect on the basis of a shared visuospatial rehearsal component (presumably absent from tone discrimination), so it does appear likely that the visual array comparisons depend to some extent on retention of visual items in the focus of attention during the inter-array interval.Recent neurophysiological studies with similar visual array comparison tasks strengthen the assumption that they rely on a capacity-limited, categorized memory for objects in the array. That required only the detection of a new color (similar to an extra-list feature; see Mewhort & Johns, 2000), not a new color/location combination. They then had to repeat the name of each picture successfully before the experiment could continue. The results that were obtained are fully compatible with the possibility that individuals with a large scope of attention are the same ones who have good control of attention; it does not provide evidence for or against that hypothesis because it does not provide a measure of the scope of attention. [PubMed] [Google Scholar]Mukunda KV, Hall VC. For example, listening span should correlate well with verbal aptitude measures, as both require linguistic skill. Each list was to be recalled aloud in the presented order. [Google Scholar]Zelazo PD, Frye D. Journal of Experimental Psychology: General. 1998;7:121–126. This was not necessarily true of Hebb's (1949) concept of short-term storage as a reverberating neural circuit. The main difference is that we propose that the focus of attention is not specific to visual processing or to its spatial aspects, but covers all modalities and codes. That could be important inasmuch as it has been shown that proactive interference grows as the span test continues (Lustig, May, & Hasher, 2001; May, Hasher, & Kane, 1999). Journal of Verbal Learning & Verbal Behavior. Third edition. Individual differences in working memory capacity and enumeration. The results were very similar to Variant 2 and will not be reported.In Variant 2, which all participants received, the instructions were to wait until the list ended and then recall as many digits as possible from the end of the list (again in forward order). The effect was highly significant in each age group and planned comparisons indicated that, within each age group, the digit-span mean was significantly higher than the mean for each of the other five WM measures, p < .01 in each case.Last, we considered that, in the visual-array comparison task, it might be easier to detect changes in color when the new color did not also appear elsewhere in the array. [PubMed] [Google Scholar]Keppel G. The WM measures that have yielded high correlations with aptitudes include separate storage and processing task components, on the assumption that WM involves both storage and processing. One square in the second array was encircled (from the onset of that array) and participants had been informed that, if any square's color had changed, it was that of the encircled square. If the change is not detected, the subject guesses “yes, there was a change” with a probability g. 69–99. Neural mechanism for the magical number 4: competitive interactions and non- linear oscillations. These shared processes, we contend, could reflect the scope of attention even in the storage-and-processing tasks.In children too young to rehearse efficiently (e.g., Naus & Ornstein, 1978; see introduction for other references), even digit span should serve as a good correlate of aptitude. [Google Scholar]Jefferies E, Lambon Ralph MA, Baddeley AD. It is also an open question whether individual differences in the measured scope of attention are due primarily to differences in the parietal mechanisms and to an intrinsic limit in the scope of attention, or due primarily to differences in frontal mechanisms and executive control needed to adjust (zoom in or out, and aim) the scope of attention. Developmental differences in visual and auditory processing of complex sentences. Capacity estimates were calculated separately using only trials in which the new color was or was not unique in the array, and using the same no-change control trials for the two sets of calculations. Cognitive Psychology. 2000;70:177–194. A possibly relevant difference in procedure is that the list length in the present procedure stayed fixed across trials in a block. 4 items in the array) correlated with the behaviorally-measured capacity at r = .78. In this case, the items to be recalled must be retrieved as separate chunks (one per item) from the activated memory representation, into the focus of attention at the time of recall.Overview of Studies We completed two developmental experiments with a range of WM tasks and scholastic and intellectual aptitude tasks. Like Cowan (2001) and Kane et al. In: Lindzey Gardner, editor. It is beyond the scope of this article to re-review it. Attention and memory: An integrated framework. As in Experiment 1, it can be seen that scope-of-attention measures provide a reasonable alternative or supplement to storage-and-processing measures. What is important for the present approach is that at least two dimensions of attention can be discerned: the control of attention and its scope. A more recent neuroimaging study by Gray, Chabris, and Braver (2003) explicitly found WM span differences in neural functioning localized in particular frontal areas, which emerged only in situations in which there was a high level of proactive interference to be overcome.Although the emphasis on the control of attention is supported by the evidence, it does not lead naturally to a meaningful measure of the capacity of WM, if that capacity is defined as a number of items in WM. The form of the activated features could include sensory, phonological, orthographic, visuospatial, semantic, or lexical features held outside of the focus of attention. These will be described in turn.Constant capacity across different decay conditions In conditions in which the activated features are short-lived, it appears that the similarity in capacity limits has held up despite very different decay parameters. Only a third of the shared variance was common to both the listening and counting span tasks, suggesting that two thirds of it could reflect individual differences in specific skills, such as auditory processing for listening span and visual processing for counting span.Last, in order to verify that the concept of a single attentional construct is a reasonable one, a structural equation model is presented in Figure 9. The assumptions just stated then lead to the following expression: $CR = k/N + [(N-k)/N]*(1 - g)$(4) The memory capacity can be estimated by adding Equations 1 and 4: $H+CR=2k/N+(N-k)/N=(k+N)/N$(5) Rearranging terms from Equation 5, In these same terms it can also be shown that, by substituting FA = 1-CR, Equation 3 based on Pashler (1988) can be restated as Thus, the present estimate of capacity (Equation 6) is equal to Pashler’s estimate (Equation 7) multiplied by the correct rejection rate, CR. (1) The participant was to type each digit upon hearing it so as to become familiar with the keypad. If the focus of attention could repeatedly access that record, it would be difficult to explain the limit to about 4 items recalled from unattended lists (Cowan, 2001; Cowan et al., 1999). A response was scored correct only for a digit placed in the box indicating its correct serial position relative to the end of the list. 1989;96:101–124. The present paper offers a rationale for measures that are simpler because they concentrate on storage, with intrinsic means to limit rehearsal and grouping.A wide variety of possibilities for the theoretical interpretation of storage-and-processing WM tasks have been discussed in the literature. Itasca, IL: Riverside Publishing Co. 1986:39. 2004;133:83–100. The digits were recorded and presented at rates of 1, 2, and 3 digits per second. Journal of Experimental Psychology. [PubMed] [Google Scholar]Hambrick DZ, Engle RW. One anomalous finding of Experiment 1 was that, among the measures of the capacity of attention, the visual-array task did not significantly correlate with scholastic measures in adults. The signal was the printed word "RECALL" along with a 1000-Hz, 73-dB(A) tone. (Note that common terminology often refers to “automatically activated” memory as synonymous with “passively held” memory.) The act of attending to representations within this activated memory presumably results in the construction of object representations in the focus of attention (cf. The first operates by diverting attention at the time of the presentation of items to be recalled; the second, by presenting these items at a rapid rate with an unpredictable endpoint; and the third, by presenting these items in a simultaneous array.Memory for ignored speech In a series of experiments (Cowan, Lichty, & Grove, 1990; Cowan, Nugent, Elliott, Ponomarev, & Saults, 1999; Cowan, Nugent, Elliott, & Saults, 2000) we have examined memory for spoken lists that were ignored while a silent, visual task requiring phonological processing was carried out. [Google Scholar]Hulme C, Muir C. This activity was found during the time between the first and second arrays and its magnitude matched the behavioral capacity limit. Indeed, Miller does not appear to have intended to make that claim (Miller, 1989), despite the way his 1956 article has often been portrayed. Replicating Cowan et al. Third, they picked up considerable variance in common with the storage-and-processing measures (Figure 7 & Figure 8) without including as much unique predictive variance; and, given that two-thirds of the unique within-age variance in g provided by the storage-and-processing measures appeared to be due to specific skills rather than abilities shared between listening and counting spans, the scope-of-attention measures generally seem to provide purer measures of WM capacity than the storage-and-processing measures.Digit span was shown to be predictive of aptitude in younger participants, but not in older ones. 1988;16:480–487. Related to this is the question of whether the observed capacity limit of about 4 chunks on average in adults (Cowan, 2001) is truly the focus of attention, or is a closely-linked, temporary store that is formed with the help of attention but is then independent of attention for its short-term maintenance (cf. (2000) found that, with the list length equal to a predetermined span for each individual, there was no overall age difference in the loss of information across test delays. We examine the relations between traditional WM measurement methods and the ones we favor.A few papers following Baddeley and Hitch (1974) were crucial in drawing the field's attention to the strong relation between individual differences in WM performance, on one hand, and individual differences in performance on psychometric indices of scholastic and intellectual aptitudes, on the other (e.g., Case, Kurland, & Goldberg, 1982; Daneman & Carpenter, 1980; Kyllonen & Christal, 1990). Modeling working memory in a unified architecture: An ACT-R perspective. Therefore, adults received blocks of trials including List Lengths 2, 3, 4, 5, and 6, and the List Length 6 trials were omitted whenever children and adults were to be compared statistically.The version of the listening span task was adapted from a task by Kail and Hall (1999), which was in turn modeled after Daneman and Carpenter (1980). However, this concept of complexity has not yet been directly related to the scope of attention. Tests based on vocabulary necessarily examine crystallized intelligence (i.e., learning), whereas tests based on nonverbal patterns allow an examination of fluid intelligence that is to some degree less influenced by specific learning opportunities. These differences have been obtained in situations in which there was some type of interference with goal maintenance to be overcome with the help of attentional control (Conway, Cowan, & Bunting, 2001; Kane et al., 2001; Kane & Engle, 2003). The assumption is that a stream of sensory memory for the most recent events forms even for unattended stimuli, and that attention can be switched to the past few seconds of that sensory memory stream to allow the conversion of that information to a categorized form for recall (Broadbent, 1958).Rapid and unpredictable presentation A sequence of items can be presented too quickly for the items to be rehearsed or grouped. [PubMed] [Google Scholar]Farmer EW, Berman JVF, Fletcher YL. Visual attention within and around the field of focal attention: A zoom lens model. Another set of regressions was carried out on the sixth-grade children and adults, who presumably could rehearse more efficiently (e.g., Ornstein & Naus, 1978). An embedded-processes model of working memory. (2002) carried out another experiment in which, in some conditions, a visual task was combined with an auditory memory load. The magical number 4 in short-term memory: A reconsideration of mental storage capacity. [PubMed] [Google Scholar]James W. Thus, with probability k/N, the change is detected. [PubMed] [Google Scholar]Booth JR, MacWhinney B, Harasaki Y. A total of 7 tasks were administered over the two experimental sessions. However, they used visual stimuli whereas Morey and Cowan used spoken stimuli for the digit load. As in Morey and Cowan, there were conditions in which verbal stimuli were presented before nonverbal stimuli and tested after the nonverbal stimuli, so that the verbal stimuli served as a memory load. Squares were placed in this area at spatial locations that were determined randomly except that the minimum separation between squares (center to center) was 2.0 degrees and no square was located within 2.0 degrees of the center of the viewing area. If one receives the digit list 1 3 8 2 4 6, for example, it might be rapidly recoded into the three two-digit numbers 13, 82, and 46 (cf. For the theoretical construct of WM, it therefore could be considered problematic if the high success of a WM measure owes more to its correlations with vocabulary measures than it does to correlation with nonverbal measures.Figure 6 shows the most theoretically meaningful profiles of correlations, which are those corrected for attenuation, including both the raw correlations (top panel) and those with age group variance partialled out (bottom panel). The stark difference from the results of the ignored-speech condition indicate a clear signature of attention during stimulus presentation in this task. Working memory (WM) is the set of mental processes holding limited information in a temporarily accessible state in service of cognition. A latent variable analysis. These correlations remained significant with age group variance partialled out. The recall cue was the same as in counting span and, when it was presented, the sentence-final words were to be recalled aloud in the order in which the sentences had been presented. By detailing some conditions in which tasks that do not include separate storage and processing components are successful in correlating with intelligence, we provide information about what mechanisms could or could not be indispensable parts of that relation. This serves as a pretest baseline against which one can compare performance on the rhyming game during spoken-digit presentations. Reaction times were recorded. There is a strong relation between this capacity and the g factor derived from verbal and nonverbal intelligence measures. The present correlational investigation does not attempt to resolve these ultimate questions, but it provides an empirical background to investigate them by documenting the relation between WM tasks with very different formats, including scope-of-attention measures that do not include a dual task but, nevertheless, correlate well with aptitude measures.A critical question is how to measure the scope of attention. However, there also was a fairly large portion shared only between the storage-and-processing and scope-of-attention measures (.13), providing support for the present theoretical approach in which these two types of measures generally provide good estimates of the scope of attention, relatively free of verbal rehearsal processes that play such a large role in digit span. To the extent that linguistic skill is needed in the aptitude test, there should be a unique relation between listening span and that aptitude. [PubMed] [Google Scholar]Chuah YML, Maybery MT. There also was a fairly large portion of variance in g unique to the storage-and-processing measures (.11).Experiment 2, prediction of g score based on four aptitude tests (Peabody Picture Vocabulary Test, Stanford-Binet Vocabulary subtest, Ravens Progressive Matrices, and Stanford-Binet Pattern Analysis subtest), conjointly by subsets of three types of WM variable. 2001;24:117–118. The development of serial short-term memory and the articulatory loop hypothesis. (The participant then typed zeros in the remaining boxes, given that zero never appeared in the stimulus list, as a way to advance the program to the next trial.) In the scoring procedure, the last non-zero item in the response was taken as the response for the final serial position, and credit was given only for digits recalled in the correct positions relative to that last one, whether or not any intervening digits in the response were the correct ones. In Session 1, tasks were carried out in the order: Stanford-Binet vocabulary and pattern analysis, visual arrays, auditory sequences, counting span, and listening span. For adults, individual differences in rehearsal and the concomitant grouping of items play a role that may mask the influence of individual differences in the scope of attention. 1996;103:403–428. The theoretical framework is based on the notion of an adjustable attentional focus and on measures of the storage capacity of attention or its scope. Trends in cognitive sciences. Pashler (1988) developed a formula to estimate the number of items in WM based on the hit and false alarm rates. Capacity limits in list item recognition: Evidence from proactive interference. 2001;54(A):31–48. This is an important issue for future research but we find it more parsimonious to assume for now that the tasks are impure.In relation to the notion that the essential quality of a successful WM task is that it measures individual differences in the ability to control attention (e.g., Engle et al., 1999; Kane et al., 2001), it is not yet clear what role the scope of attention plays in a unified theory of the deployment of attention in WM tasks. One second later the word "READY" appeared for 2 s, after which a spoken list began. If the participant was correct on at least 9 of 12, testing proceeded to a set size one larger. An alternative possibility is that the basic scope of attention itself, and not only the control of attention, varies among individuals. 1993;21:193–197. (in press) [PubMed] [Google Scholar]Cowan N, Kail R. In an ANOVA of capacity estimates with age group as a between-participant factor and condition (change to a unique vs. (3) On tasks involving memory retrieval, dividing attention impairs performance in individuals with high WM spans but has little effect on individuals with low WM spans (Rosen & Engle, 1997). In Experiment 2, in prediction of g and of the within-age portion of g, there was just a slight advantage for the storage-and-processing measures (.56 and .24, respectively) over scope-of-attention measures (.45 and .18). Short-term memory: A brief commentary. 1956;63:81–97. Second, as proposed above, the absence of effective rehearsal in children may make digit span a purer measure of the scope of attention than it is in adults.A second experiment was conducted to overcome limitations in the first one. [Google Scholar]Andrews G, Halford GS. Table 1 and Figure 1). It would be helpful in future work to determine what the definitive measurements of the episodic buffer are; whether these measurements can be made relatively free of contamination from domain-specific skills; whether these measurements change with childhood development and, if so, why and how they change; and whether they capture the same common variance in aptitudes that the storage-and-processing measures and the scope-of-attention measures capture. Although it could be argued that there is no clear "winner, " this sort of examination provides a picture of some benefits and drawbacks of various WM measures, and it illustrates strengths of some measures that do not include separate storage and processing components.Last, as in Experiment 1, there were no significant differences between the correlations resulting from visual-array capacities based on trials with changes to a unique versus a non-unique stimulus. (1999), participants carried out a task in which the learned name of a picture in the center of the computer screen rhymed with the learned name of one of four peripheral pictures (to be selected with a mouse click, followed by a new central picture to be judged). [PubMed] [Google Scholar]Baddeley A. [Google Scholar]Barrouillet P, Bernardin S, Camos V. [Google Scholar]Kyllonen PC, Christal RE. 2000;53A:626–646. These correlations demonstrate that the storage-and-processing tasks were not consistently more successful than the simple spans in accounting for within-age variance in reading recognition. Over the top: Are there exceptions to the basic capacity limit? These measures are included here in order to examine their relation to less conventional tasks in the same study that have not been reported previously: the running-span, ignored-speech, and visual-array tasks that we used to assess the capacity of the focus of attention.This study was conducted with funding from NIH Grant HD-21338 awarded to the first author. Limited processing capacity constrains the storage of unrelated sets of words and retrieval from natural categories. To construct this table, one set of regressions was carried out on the two age groups considered too young to rehearse efficiently, the children in second and fourth grades. In particular, in each of these tasks, 2-item practice trials (two of them in counting span, three in listening span) were followed by three trials in a row at each list length, starting with 2-item lists and increasing until the participant failed to recall any of the three lists of a particular length correctly. 2004;428:749–751. We will argue that the research literature provides hints that the strengths can be retained without using storage-and-processing measures. Acta Psychologica. Work is ongoing in our laboratory and in other laboratories to determine whether this sort of task correlates well with a wider array of aptitude tasks. It might be hypothesized, then, that visual-array comparisons do not include many verbal or auditory processing skills but do pick up variance that could be attributed to the general scope of attention.This suggestion also must be viewed in light of two other recent studies that involve visual arrays and fail to provide support for the importance of the scope of attention. 2000;129:262–284. On the nature of echoic persistence: Experiments with running memory. Most lists were to be ignored but occasionally the rhyming game was replaced by a recall probe, at which time the participant was to use the key pad to recall the last list of digits. [PubMed] [Google Scholar]Kail R, Hall LK. However, correlations and regressions (below) strongly support its existence.Experiment 1 showed that, in predicting scholastic abilities in adults, there was considerable variance shared between storage-and-processing tasks, on one hand, and scope-of-attention tasks, on the other hand. Hove, U.K: Erlbaum Associates, Ltd.; 1996. [PubMed] [Google Scholar]Posner MI, Rafal RD, Choate LS, Vaughan J. The .09 of the variance in high school grades percentile unique to the scope-of-attention measures could be attributed to specific skills unique to the two verbal measures (.06) and to visual arrays (.04; the three measures summing to .10 due to rounding error), with none due to variance shared between all three. The role of working memory capacity in retrieval. This study clearly shows that high- and low-span individuals differ in something other than the scope of attention, but it does not indicate that they do not also differ on the scope of attention. It is possible that the difficulty of the storage-and-processing tasks reduces their predictive quality relative to the other measures, which do not involve a simultaneous dual task. The cue circle specifying the target square was black and 1 pixel thick, with a diameter of 1.5 degrees of visual angle. The proposal is that the relevant portion of the variance in the popular storage-and-processing measures (e.g., Daneman & Carpenter, 1980; Turner & Engle, 1989) also reflects this scope of attention.Based on this proposal, three basic expectations were generated and will be evaluated in turn. However, that evidence is still sparse and not well-integrated theoretically. Table 1 of Kail and Hall can be used to calculate the correlations between span measures and reading recognition with age partialled out. When necessary, it might zoom in to hold on to a goal in the face of interference, and perhaps a minimum of related data that is required. The main results of that study, reproduced in Figure 1, shows that the capacity limit for ignored lists (solid lines) was fairly constant across list lengths and increased with age. Baddeley, 1986).Limiting the functioning of attention during encoding and maintenance If we wish to examine how many chunks of information can be formed from the features in activated memory after they are retrieved into the focus of attention at the time of recall, it is necessary to know the nature of information in the activated memory record. [PubMed] [Google Scholar]Cowan N, Wood NL, Wood PK, Keller TA, Nugent LD, Keller CV. The domain-generality of WM has also been emphasized by Kane et al. In future psychometric research with this procedure, it would be helpful to increase the number of trials per participant.The ignored-speech average was about one item lower than in past research (cf. In contrast, the visual-array comparison task, which was not predictive in adults, was a good predictor in children. Persistence of memory for ignored lists of digits: Areas of developmental constancy and change. In contrast, in Morey and Cowan (2004), the verbal memory load was repeated correctly on only 45% of the trials, a much more difficult load. Inhibition of return: Neural basis and function. (Other areas responded in a load-dependent manner but the relation to the behavioral limit was not as clear as for these areas.) The results suggest that the scope of attention in this task is limited not because of a failure of attentional control, but because of an inherent limitation in how many objects can be included in WM at once.Simple spans and storage-and-processing spans as potential scope-of-attention measures It is important to note that a theory of WM capacity limits based primarily on the scope of attention might be able to explain results from more traditional measures of WM, too. It also can account for the finding that the proportion of the retention interval that is filled with a retrieval task, even an easy one such as reading off numerals on the screen, is critical (Barrouillet et al., 2004). Object-centered inhibition of return of visual attention. Performance levels on these “storage-and-processing” types of tasks are highly interrelated. [PubMed] [Google Scholar]Darwin CJ, Turvey MT, Crowder RG. 1970;1:149–156. In the running-span task, the method was restricted to the one that had been used across ages in Experiment 1, i.e., Variant 2.We also considered that, in Experiment 1, the digit-span and storage-and-processing span measures were collected with gradually increasing list lengths, whereas the capacity-of-attention measures were collected with set sizes either fixed within a block or mixed together. If this binding process develops with age in childhood, the difference between changes to a color that was versus was not unique in the array might be larger for younger participants. After the final tone in the first series presented on a trial, there was a 1-s silent period (with a fixation cross) and then a second tone series that was identical to the first or differed in the frequency of one tone. (7) The silent rhyming game was carried out with no auditory stimuli for 1 min as a post-test baseline.The two versions of the running-span task in adults yielded roughly comparable results but the correlations with criterion measures were slightly higher for Version 2, the version that the children also received. In Experiment 1, digit span was more successful than any other measure in the prediction of within-age variance in CAT scores in third- and fifth-grade children (Figure 5), whereas it was substantially poorer than the other WM measures in the prediction of the ACT and high school grades in adults (Figure 3 & Figure 4). In Experiment 1, the scholastic measures could only be examined in children and adults separately and they were applied measures. [PubMed] [Google Scholar]Hockey R. The counting span, which had performed quite respectably in adults, was the only WM variable that was not significantly correlated with the CAT composite score (or any of the subscores). Although passive storage sometimes may suffice, it also may be necessary to use attention as a holding device (e.g., Anderson & Lebière, 1998; Lovett, Reder, & Lebière, 1999). The 1-s retention interval provided the preferred index of how much ignored information can be pulled from the sensory memory stream into WM when attention is redirected to the digit stream, whereas the 5-s retention interval provided data on the rate of sensory memory loss over time. 2003;18:240–249. Working memory and thinking. Bayliss et al. Ornstein & Naus, 1978). The diagram is based on regressions shown in Table 9. A feature model of immediate memory. [PubMed] [Google Scholar]Wilding J. For example, in adults, the estimated mean capacity for 10- item arrays was 0.32 items fewer than for 8-item arrays, but the SD of that difference was 2.43 items, more than for the other measures. Six strands of research on this topic can be enumerated. The importance of such study is partly that it can help in predicting and clarifying childhood aptitudes and disabilities (e.g., Swanson, in press), and partly that it can help in clarifying the processes of WM per se. 2003;65:888–900. Steven's handbook of experimental psychology. That is to be expected if the correlations are due to the involvement of processes of attention that cut across content domains. [PubMed] [Google Scholar]Cowan N. [PubMed] [Google Scholar]Hebb DO. We provide a theoretical framework to understand the relation between WM and aptitude measures. The tones used on a trial were drawn randomly from a set of 7, with frequencies of 500, 552.50, 610.51, 674.61, 745.44, 823.71, and 910.20 Hz (i.e., in 10.5% increments), played at 74 – 76 dB(A) over audiological headphones as measured by a sound level meter with an earphone coupler. (5) The silent rhyming game was carried out with no auditory stimuli for 1 min. Toward that end, an adjustable-attention framework will be described. However, pilot data indicated that Variant 1 was too difficult for the younger children, who therefore only completed Variant 2. Such a capacity would not replace the attention-free stores of Baddeley (1986) as the two presumably could co-exist (i.e., phonological and visuospatial buffers might exist apart from attention).At least four related assumptions about this concept of the scope of attention are subsumed under the attention-adjustment hypothesis under investigation here: (1) that there is a limit in the capacity of the focus of attention, (2) that this limit varies between individuals, (3) that measures of this capacity are theoretically and empirically related to storage-and-processing measures of WM, and (4) that the common variance between these measures is related to intellectual aptitude measures. The second method of scoring involved the numerical estimate of the number correct or number of items in WM taken from whatever list length or set size produced the highest such estimate. However, scope-of-attention measures were found to have certain advantages. Wiley; 1975. (2004), we find it most parsimonious to assume that there is a general, amodal attentional resource, which has been assumed by other investigators for very different reasons as well (e.g., Tombu & Jolicoeur, 2003). 1996;3:422–433. What is more revealing is the success of visual-array comparisons as a correlate of the within-age variance in all of the intelligence measures in Experiment 2, as shown in Table 8. In Experiment 2, we used two verbal and two nonverbal intelligence measures: the vocabulary and pattern-analysis subtests of the Stanford-Binet intelligence scale (Thorndike, Hagen, & Sattler, 1986), the Peabody Picture Vocabulary Test (Dunn & Dunn, 1997), and Ravens' Progressive Matrices (Raven, Raven, & Court, 1998).Our main expectations for the study are of three types.Expectation 1: Predictive Value of Scope-of-Attention Tasks Our basic expectation is that the storage-and-processing tasks and the scope-of-attention tasks should have much in common. Unlike the other tasks we have examined, and unlike Sperling's task, it is designed in such a way that there is only one response to be made on every trial, avoiding the possibility of output interference. (4) The silent rhyming game was practiced with no auditory stimuli until 6 correct matches were made. [Google Scholar]Luck SJ, Vogel EK. This is the case in recall from a semantic category (Broadbrent, 1975; Graesser & Mander, 1978), from a sequence of digits memorized by a mnemonic expert (Wilding, 2001), and from chess boards that remain present while they are copied (Gobet & Simon, 2000). In adults, neither measure correlated with high school grades or ACT composite scores.One of the main hypotheses of the study was that storage-and-processing measures and scope-of-attention measures share substantial common variance in the prediction of scholastic abilities. Vol. Sources of developmental change in children's word-problem performance. Daneman and Carpenter (1980) suggested that, given an assumed structure of WM in which storage and processing shared resources, an adequate test of WM must tax both storage and processing. [Google Scholar]Haarman HJ, Davelaar EJ, Usher M. [Google Scholar]Cahan S, Cohen N. However, it is possible that there are individual differences in storage itself, even with linguistic processing equated. [PubMed] [Google Scholar]Ashcraft MH, Kirk EP. 2000;24:651–682. The effects of aging and first-grade schooling on the development of phonological awareness. These means are shown in Table 1, along with means for the aptitude measures. Baddeley, 1986; Naveh-Benjamin & Jonides, 1984). The square colors were red, blue, violet, green, yellow, black, and white, and each square was assigned a color randomly with replacement (i.e., there was no restriction against the same color appearing more than once in the same array, a method that requires memory of the location of each color). For digit span, this may occur because of a reliance on phonological memory, which is instrumental in vocabulary acquisition (Baddeley, Gathercole, & Papagno, 1998). [Google Scholar]Miyake A, Friedman NP, Rettinger DA, Shah P, Hegarty M. However, this skill variance should not be general across WM tasks. The classic example of this is in tests of memory for the unattended channel in selective listening with dichotic presentation (e.g., Glucksberg & Cowen, 1970; Norman, 1969). non-unique color) as a within-participant factor, it was easier to detect a change to a unique color (M = 5.49, SEM = 0.15) than to a non-unique one (M = 4.03, SEM = 0.12), F(1, 134) = 159.27, MSE = 0.85, p < .01. For these variables, respectively, the third-grade means (with SEMs) were 5.08 (0.16), 2.84 (0.18), 1.95 (0.15), 2.03 (0.14), 1.65 (0.16), and 5.51 (0.41). [Google Scholar]Gathercole SE, Adams A-M, Hitch GJ. In: Ornstein PA, editor. A great deal of research described in the introduction reinforces the notion that an important concept underlying these findings is that individual differences in the measured scope of attention are important for individual differences in aptitudes. Consequently, we expected that it should correlate with aptitudes just about as well as other WM spans in young children (in second through fourth grades), but not in older, sixth-grade children or in adults.It may seem counter to this last prediction that Kail and Hall (2001) found that simple spans (for digits, letters, and words) did not provide as good a prediction of a criterion task as did more complex spans, including listening and reading span and a "least-number span" task in which multiple lists were presented and the lowest number in each list had to be identified and retained for subsequent recall. [PubMed] [Google Scholar]Pollack I, Johnson IB, Knaff PR. On every trial in the condition that we use, an array of colored squares was presented briefly, followed after an inter-stimulus interval by a second array similar to the first. 2000 Edition. The list was accompanied by an empty, red-bordered box during presentation, and was followed by recall cues comprising a green-bordered box and a tone, occurring simultaneously and in pace with the list items. [PubMed] [Google Scholar]Glucksberg S, Cowen GN., Jr Memory for nonattended auditory material. Design and analysis: A researcher’s handbook. Spoken sentences were presented through speakers at 66 – 68 dB(A). 1984;10:369–385. The list included 12 to 20 random, spoken digits (from the set 1 – 9) presented via computer at a rapid pace of four digits per second. 2002. [Google Scholar]Lustig C, May CP, Hasher L. Psychological Monographs. A meta-analysis. Second, cross-age differences in processing can shed light on the mechanisms of WM. The role of attention in the development of short-term memory: Age differences in the verbal span of apprehension. [PubMed] [Google Scholar]Sirevaag EJ, Kramer AF, Coles MGH, Donchin E. First, it was only the nonverbal scope-of-attention measures that were found to correlate significantly with all four of the aptitude tests even when age- group variance was removed (Table 8). That concept has played a central role in neoPiagetian theories of cognitive development, in which developmental maturation of thought is attributed to an increase in the available WM space, either because the space increases with maturation (Pascual-Leone, 1970) or because of increased efficiency in the use of the available space (Case et al., 1982). This rehearsal and grouping is presumably prevented in the other WM tasks by various imposed processing difficulties, as discussed in the introduction.There is now a considerable variety of studies in which relationships between different types of WM procedures and intellectual aptitudes, and their development, have been assessed (e.g., Ashcraft & Kirk, 2001; Booth, MacWhinney, & Harasaki, 2000; Caplan & Waters, 1999; Conway et al., 2002; Cowan et al., 2003; Daneman & Hannon, 2001; Daneman & Merikle, 1996; Engle et al., 1999; Fry & Hale, 1996; Gathercole & Pickering, 2000; Haarman, Davelaar, & Usher, 2003; Hedden & Park, 2003; Hitch et al., 2001; Hutton & Towse, 2001; Kyllonen & Christal, 1990; Lustig et al., 2001; Miyake, Friedman, Rettinger, Shah, & Hegarty, 2001; Oberauer et al., 2002; Salthouse, 1996; Swanson, 1996). Numbers within the overlapping sections of the circles do not represent collinarity between the variables, but portions of CAT variance that are predicted in common by the overlapping WM variables.The relatively poor predictive quality of the storage-and-processing measures in children would not be expected based on past literature, though that literature is sparse in children. Rehearsal processes in children's memory. [Google Scholar]Jevons WS. Also, Cowan et al. Given the similarity in results with the two scoring methods and the greater methodological consistency between measures with the second method, it will be used in all subsequent descriptions. In contrast, according to Pashler's estimate, the means (and SDs) were 3.23 (0.86), 3.64 (2.19), 4.18 (2.90), and 4.18 (2.71) items. At slower rates, an active strategy was advantageous whereas, at faster rates, a passive strategy became advantageous. [Google Scholar]Raven J, Raven JC, Court JH. 2002;9:637–671. The scope of attention is a simple, traditional concept related to the notion of WM and we believe that its value as a construct has been reinforced by these findings.Although these findings point toward an agenda for research, there are important points that they leave unresolved. The role of interference in memory span. Based on subsequent entries (97), our projection for 2001–2005 is 160, a tenfold increase from 20 years previous.The observation of a strong relation between WM and aptitude tasks has been gained at a theoretical cost, though. Examined in that way, listening span's unique contribution was critical, ΔR2 = .09, p < .05, whereas counting span contributed nothing and the shared variance between them accounted for only .01. Oxford, U.K: Oxford Psychologists Press Ltd.; 1998. Thus, counting span does not require the same degree of linguistic skill as listening span, though it does require some arithmetic skill and, perhaps, spatial skill. On the nature of forgetting and the processing-storage relationship in reading span performance. [PubMed] [Google Scholar]Cowan N, Saults JS, Elliott EM, Moreno M. We also carried out regressions using factor scores for the storage-and-processing measures and the scope-of-attention measures, based on factor analyses yielding single-factor solutions. Cowan (2001) reviewed a great deal of literature in support of the notion that there is a form of storage that typically can include 3 to 5 separate units, or chunks, of information in normal adults, and proposed that the special form of storage limit may be the capacity of the focus of attention, i.e., the scope of attention. Familiarity and visual change detection. The storage-and-processing tasks could be the best WM predictors of aptitudes but still could be relatively undesirable tasks if much of their predictive value comes from mechanisms that are not central to the concept of WM (e.g., domain-specific skill in reading or arithmetic). (unpublished) [Google Scholar]Copeland DE, Radvansky GA. Subitizing and similarity: Toward a pattern-matching theory of enumeration. Working- memory capacity and the control of attention: The contributions of goal neglect, response competition, and task set to Stroop interference. New York: Academic Press; 1968. [PubMed] [Google Scholar]Case R, Kurland DM, Goldberg J. [PubMed] [Google Scholar]Kane MJ, Bleckley MK, Conway ARA, Engle RW. [PubMed] [Google Scholar]Halford GS, Wilson WH, Phillips S. There is no evidence in these correlations of a property that consistently distinguishes storage-and-processing measures from scope-of-attention measures of WM.The belief that both types of measures capture substantial variance that cuts across content domains is reinforced by correlations between visual-array comparisons and measures based on acoustically-presented materials. This main phase of the experiment included 6 trials with 5-digit lists and then 6 trials with 7-digit lists (for each list length, beginning with a 1-s retention interval and with the length of the retention intervals alternating between 1 and 5 s).The number of digits in a list and the inter-list intervals and retention intervals differed from those of Cowan et al. Our concept might also be related to the model of LaBerge and Brown (1989), who propose that there is a gradient of processing that becomes less intense as one gets further from the focus of attention. In this experiment, it is untenable to plot the capacities separately for each set size, given that testing for each participant stopped when performance fell under 75% correct and some participants ended at quite short set sizes.Experiment 2, Means and Standard Errors of Key Variables in each Age Group and Age Effects from ANOVAsGrade 2Grade 4Grade 6AdultAgeEffectMeasureMeanSEMMeanSEMMeanSEMMeanSEMF valueώ2Working-Memory MeasuresDigit Span4.700.164.940.115.370.146.430.2222.090.33Counting Span2.750.193.810.154.050.194.460.1616.110.26Listening Span1.740.102.290.092.680.123.330.1531.040.42Running Span1.700.142.420.102.740.153.230.1023.660.35Auditory Sequences2.830.243.330.203.990.263.740.224.530.08Visual Arrays3.400.254.650.254.840.265.770.3311.540.20Scholastic Aptitude MeasuresPPVT124.763.50145.942.95162.362.20181.171.1577.010.64S-B Vocabulary23.100.5926.860.5729.300.5836.240.6579.400.65Ravens Progressive Matrices31.031.8338.391.2641.791.3846.031.4117.300.28S-B Pattern Analysis27.031.2134.751.0436.420.9339.720.7226.540.38As in Experiment 1, separate 1-way ANOVAs were conducted within each age group on the six measures of WM. According to the theoretical assumption that each scope-of-attention task measures the number of chunks held and the assumption that the capacity limit is general across modalities and domains, no difference in means would be expected. The diagram is based on regressions shown in Table 5. Equation 1 remains valid. For a criterion variable and any three predictors A, B, and C, one needs stepwise regressions with the three variables entered in all six possible orders (ABC, ACB, BAC, BCA, CAB, CBA). 1998;105:158–173. Third, digit span should pick up more unique variance for children than for adults. It would be difficult to attend to the boring and repetitive spoken lists, most of which require no response, during the more interesting rhyming game, because of habituation of orienting to the sounds (e.g., Sokolov, 1963; Cowan, 1988).Second, the suggestion that sensory memory decay might have been the limiting factor does not agree with the findings from the short test delays that Cowan et al. Modality effects and the structure of short-term verbal memory. In Study 2 they were, for digit and word spans, .34 and .20; for reading, listening, and least-number spans, .32, .29, and .31, respectively.) One would expect even less advantage for storage-and-processing WM tasks in the younger children examined separately. Journal of Experimental Child Psychology. As discussed above, this is done essentially by overwhelming or distracting attention at the time that stimuli are presented, which means that items cannot be grouped together. (2000), there were no age differences in the list-wide rate of loss over time, and 5-s results will not be reported further. (For a mathematical model of WM based on this concept, see Usher, Haarmann, Cohen, & Horn, 2001; for relevant experimental work see Chen, 2003.) This concept is related to the zoom lens model of attention of Eriksen and St. James (1986). However, this was impossible for two of the measures of the scope of attention (ignored speech and running span) because no stimulus length produced 50% correct performance. There were three practice trials with two screens each (i.e., List Length 2) and then three blocks of test trials. Running memory span (Pollack, Johnson, & Knaff, 1959) is a procedure in which a list of an unpredictable, long length is presented, the task being to recall as many items from the end of the list as possible after the list terminates. The interaction with age group did not approach significance. Individual and age-related differences in children’s working memory. Journal of Educational Psychology. On balance, though, the results are consistent with the view that variance unique to either storage-and-processing measures or scope-of-attention measures primarily reflects specific skills, whereas the variance shared between them is more indicative of the processes rightly conceived as WM. (1982). Of particular interest, the raw correlations between visual arrays and listening span were hefty (in Experiments 1 & 2, r = .50 and r = .51, respectively). In particular, if H = 1.0 then, according to Equation 3, k = N no matter what the value of FA. Two scorers independently added the test section scores and any discrepancies or problems in either administering the test or scoring it were discussed and

resolved.Despite minor differences from Experiment 1 in the way in which the data were collected, scoring of each WM measure in the present experiment was done in exactly the same manner as in Experiment 1. A central capacity sharing model of dual-task performance. Although it is possible to carry out a learning study to estimate how the items are grouped into chunks in serial recall (Cowan, Chen, & Rouder, 2004), a simpler method is to limit grouping and rehearsal processes during presentation and maintenance of the stimuli. Training included learning the labels of pictures of common items, to be used in several other phases.In the main phase, participants carried out a silent game in which they had to indicate (with a mouse click) which of four peripheral pictures rhymed with a central picture, as quickly as possible, with the next rhyming-task trial beginning immediately after an answer was given to the previous one. What limits children's working memory span? [Google Scholar]Cowan N, Keller T, Hulme C, Roodenrys S, McDougall S, Rack J. [PubMed] [Google Scholar]Cowan N, Nugent LD, Elliott EM, Ponomarev I, Saults JS. The episodic buffer: a new component of working memory? Given these possibilities, it is important to investigate what we might learn from potentially simpler tasks.There is already some evidence that some WM tasks that do not include separate storage and processing components are nevertheless capable of yielding relatively high correlations with aptitude tests. A great deal of recent research has converged on the importance of the control of attention in carrying out the standard type of WM task involving separate storage and processing components. NY: Pergamon Press; 1963. In Experiment 1, the .10 of the variance in the prediction of ACT scores unique to the storage-and-processing measures was entirely the result of listening-span variance. Thus, as predicted, digit span is much more predictive in children than it is in adults. It is not at all clear why the working-memory tasks work. Verbal working memory and sentence comprehension. The two largest proportions of within-age variance in g were those shared between storage-and-processing tasks and scope-of-attention tasks (.09) and unique to storage-and-processing tasks (.09). Zelazo & Frye, 1998). 2001;29:1–9. Performance on a task can be impaired by a concurrent task if there is a need for the tasks to share a general, cross-domain resource such as attention, specific resources such as verbal or spatial processing, or both of these (for discussion see Cowan, 2001). New York: Oxford University Press; 1995. No specific sum was repeated more than once within a trial.Participants progressed through the program by pressing the space bar when ready for the next phase of a trial. Table 1 also shows significant age effects for all WM measures.Although most means matched expectations and were similar with the two scoring methods, a few discrepancies should be discussed. Further investigation indicated that this difference occurred because performance was quite variable from one set size to another within an individual. Logie, Della Sala, and Wynn (2000) found that visual codes play a role in verbal recall. Reasoning ability is (little more than) working-memory capacity?! Intelligence. The development of executive function in childhood. 2004;133:189–217. If both attentional control and the scope of attention vary among individuals, then additional questions include (1) how interrelated or independent these faculties are, and (2) to what extent each of them is fundamentally responsible for individual differences in aptitudes.An examination of task differences seems relevant to these questions. (6) The main phase of the task, described above, was conducted, comprising 12 trials of memory for ignored spoken lists. Theoretically, it could contribute a great deal in both kinds of measures because both kinds prevent rehearsal and grouping during presentation of the list, in various ways explained in the introduction.For children, digit span did strikingly well in predicting CAT scores; better than the other variables did and much better than digit span did in adults. (2001) showed that spatial storage, with or without concurrent processing, tends to be closely related to executive function, in contrast to the separation between phonological storage and executive function. Each trial ended with response feedback and participants were encouraged to take breaks between trials as needed.The memory for ignored speech task examines memory for spoken digits when attention is presumably directed away from the digits until after their presentation ends, so that attention must then be used to retrieve unprocessed information from sensory memory. (2000) examined the serial position effects across test delays and found severe forgetting of information from both the primacy and the recency portions of the list, in contrast to the stability of primacy effects across test delays that is found for attended lists (Jahnke, 1968). The only restriction on randomization was that, throughout each list, a digit was never repeated within a moving window of consecutive digits whose size equaled the number of response boxes. Using himself as the subject, he found that only a small number could be counted. [PubMed] [Google Scholar]Miyake A, Shah P, editors. When visual and verbal memories compete: Evidence of cross-domain limits in working memory. A latent variable analysis of working memory capacity, short-term memory capacity, processing speed, and general fluid intelligence. Intelligence. Subitizing speed, subitizing range, counting speed, the Stroop effect, and aging: Capacity differences and speed equivalence. [PubMed] [Google Scholar]Bayliss DM, Jarrold C, Gunn DM, Baddeley AD. The issue clearly warrants re-examination with other aptitude tasks.Experiment 1: Means and Standard Errors for Key Variables and Age Effects from ANOVAsMaximumGrade 3Grade 5AdultsAge EffectMeasurePossibleMeanSEMMeanSEMMeanSEMFω2WM Measures Digit Span94.610.134.980.146.790.1475.350.52 Counting Span52.810.133.400.123.620.0814.860.176--------3.860.10 Listening Span52.000.122.700.153.500.1236.290.346--------3.700.14 Running Span72.440.152.800.133.870.0943.250.38 Ignored Speech72.010.181.980.152.670.147.110.08 Visual Arrays103.690.284.140.235.670.1824.370.25Scholastic Ability MeasuresCognitive Abilities Test (CAT) Composite--115.242.33113.402.37-------- Verbal--110.062.34111.152.38-------- Quantitative--112.272.39112.312.15-------- Nonverbal--116.092.38113.282.42--------High SchoolGrades Percentile100--------77.112.50----American College Test (ACT) Composite---------25.110.54---- English---------24.950.61---- Math---------23.910.67---- Reading---------26.740.65---- Science---------24.120.59----Participants Only participants who attended two sessions and, in those sessions, completed all WM tests were included in the final sample. Working memory: The multiple-component model. Nov, Attentional limitations in visual short-term memory. In our experiments we have used digitally compressed speech to achieve a rate of 4 digits per second so that an active strategy cannot be used to advantage. Behavioral and Brain Sciences. Those who did (N = 137) included 37 third-grade children (17 male, 20 female; mean age = 105.46 months, ranging from 97 to 121 months, SD = 5.36), 37 fifth-grade children (15 male, 22 female; mean age = 128.65 months, ranging from 119 to 143 months, SD = 5.85), and 63 adults (24 male, 39 female; mean age = 238.65 months, ranging from 217 to 512 months, SD = 41.06). 1992;24:175–219. 2001;29:484–492. One component is a developmental increase in the scope of attention, contributing to all of the WM measures. Raven Manual: Section 3. Organization of behavior. Capacity limit of visual short-term memory in human posterior parietal cortex. This finding theoretically could be interpreted in at least two ways. 1998;127:141–160. 2004;11:296–301. This was expected because digit span is not a good measure of capacity in participants old enough to rehearse. Running memory span. In Experiment 2, digit span was at least as good as the other measures in predicting within-age variance in g for the younger two age groups, whereas it was not predictive at all in the older two age groups. To investigate this question, we entered all WM measures into the regression in a single step except for one storage-and-processing measure, and then examined the ΔR2 value for the addition of the final measure. [Google Scholar]Broadbent DE. It includes data only for those set sizes and list lengths at which all participants in an age group were tested. [PubMed] [Google Scholar]Daneman M, Merikle PM. [Google Scholar]Ornstein PA, Naus MJ. Atomic components of thought. [Google Scholar]Logan GD. [PubMed] [Google Scholar]Cowan N, Johnson TD, Saults JS. This measure provides capacity estimates in the same range as a wide variety of other tasks reviewed by Cowan (2001) and is fairly constant across array set sizes above the capacity limit of 3 to 4 items.Presumably, the arrays are presented too briefly for participants to encode items verbally and recall them as a list (e.g., top-left-blue, middle-green, and so on). Search of a popular electronic data base (PsycInfo) carried out on January 30, 2004 showed that the number of articles or dissertations that included both the phrase "working memory" and the phrase "individual differences" in the title or abstract have increased steadily since 1980. From these panels, the two measures that might be considered problematic are digit span and listening span. The procedure was very similar to that of Cowan et al. The unique variance thus reflected some specific skill (e.g., language comprehension) and can be considered an impurity of this storage-and-processing measure, not a theoretical strength.In the prediction of high school grades, the total variance predicted by the storage-and-processing measures was .13; by the scope-of-attention measures, .18; and by digit span, .02. Perception and communication. Although acquired knowledge is extremely important for both WM tasks and aptitude tasks (e.g., Ericsson & Kintsch, 1995), correlations between WM tasks and aptitude tasks remain even when the role of knowledge is measured and controlled for (Hambrick & Engle, 2001). Cambridge, U.K: Cambridge University Press; 1999. [PubMed] [Google Scholar]Pashler H, Johnston JC, Ruthruff E. Although attention is directed to the list during its presentation, it is rendered ineffective in producing rehearsal or grouping, so that the results are functionally equivalent to memory for ignored speech.Visual-array comparisons The visual array comparison task of Luck and Vogel (1997), like the task of Sperling (1960), presents a simultaneous array of objects to be remembered on every trial, typically too many to be combined into a smaller number of groups in the time available. Upper Saddle River, NJ: Prentice Hall; 1991. Numbers within the overlapping sections of the circles do not represent collinarity between the variables, but portions of within-age-group g variance that are predicted in common by the WM variables shown as overlapping.The distribution of within-age variance, shown in Figure 8, removes age-related changes in skills. The difference between patterns of performance for visual arrays versus auditory sequences was unanticipated, but it could be explained on the grounds that new repetitions in tones could be used to detect a change in pattern.Table 7 presents raw correlations, reliabilities of the measures and, above the diagonal, correlations corrected for attenuation. This suggests that low-span individuals do not make use of attention in the same way that high-span individuals do within these tasks. Also, some procedures include a cue to examine only one object within the memory record of an array (e.g., Luck & Vogel, 1997) or list (Cowan, Johnson, & Saults, in press), yet a similar capacity limit of about 4 items is obtained.Finally, in procedures in which recall is from the long-term memory record, so that the memory representation does not decay, we see that the pattern of recall looks different than when recall is from a short-term record. SPM29) [Google Scholar]Rosen VM, Engle RW. [PubMed] [Google Scholar]Oberauer K. Children were also rewarded with stickers at several points. 1999;73:7–44. The adults were psychology students who received course credit.Apparatus, Stimuli, and Procedure The experimental sessions took place in sound-attenuated booths. Run 2 followed the same procedure, but without practice trials.Storage-an d-processing tasks The version of the counting span task was adapted from Conway, Bottoms, Nysse, Haegerich, and Davis (unpublished), which was in turn modeled upon Case et al. All of the WM measures correlated with the ACT composite scores except visualarray comparisons.Experiment 1, Correlations Among Working-Memory and Scholastic Measures In Adults, and Reliability EstimatesDSCSLSRSISVAHGACAEAMARDigit Span (DS).88.47.71.74.89.38.16.42Counting Span (CS).32*.51.61.58.83.37.45.45Listening Span (LS).58*.38*.77.57.70.48.30.61Running Span (RS).65*.39*.47*.86.67.32.38.40Ignored Speech (IS).68*.48*.50*.51*.66.45.38.48Visual Arrays (VA).27*.19.31*.22.27*.55-.10.21High School Grades (HG).15.32*.26.36*.31*-.08--.60ACT Composite (AC).37*.30*.50*.35*.37*.14.56*.87 English (AE).32*.30*.37*.41*.29*.11.47*.86* Math (AM).41*.35*.51*.32*.40*.21.48*.86*.72* Reading (AR).32*.03.33*.24*.24*.04.50*.89*.56*.54* Science (AS).15.26.44*.13*.27*.13.50*.89*.64*.72*67*Table 3 also shows that, for high school grades, the only significant correlations were with counting span (r = .32), running span (r = .36), and memory for ignored speech (r = .31). In control conditions in which the visual task was to be carried out alone, just before and just after the ignored-speech task, performance closely matched the level on the same task in the presence of speech to be ignored. In all children taken together, for maximal digit span SD = 0.83, whereas in adults, SD = 1.11. This sort of task serves the same purpose as memory for the ignored channel in selective listening (Glucksberg & Cowen, 1970; Norman, 1969) except that it avoids the problem of acoustic masking between channels. Restricted attentional capacity between sensory modalities. The extralist-feature effect: Evidence against item matching in short-term recognition memory. Clearly, as well, a large portion of the variance was age-group variance, given the lower levels of many of the correlations with age group partialled out.Experiment 1, Correlations Between Measures of Working MemoryDSCSLSRSISVADigit Span (DS).94.21*.48*.63*.61*.29*Counting Span (CS).43*.63.37*.27*.26*.19*Listening Span (LS).69*.52*.83.32*.37*.29*Running Span (RS).78*.44*.56*.92.53*.26*Ignored Speech (IS).62*.34*.45*.57*.70.24*Visual Arrays (VA).53*.36*.50*.48*.34*.66Table 3 shows the raw correlations among measures in adults, along with reliabilities of the measures (diagonal) and correlations corrected for attenuation, for which significance tests are unavailable. Evolving conceptions of memory storage, selective attention, and their mutual constraints within the human information processing system. All age effects were significant; given that raw scores were used for the aptitude tests, the age effects for these were significant along with those for the WM tests. Cognitive Neuropsychology. This remains a key question for further research.It also will be important to determine how the concept of the scope of attention influences cognitive capabilities. 2004;428:751–754. In: Pashler H, Yantis S, editors. They therefore designed reading- and listening-span methods in which a processing task (comprehending sentences) was to be carried out interleaved between items in a storage task (retaining the last word of each sentence for later recall). [PubMed] [Google Scholar]Shiffrin RM. This procedure began with five boxes, at which there were two practice trials followed by nine test trials. We have, metaphorically, provided a barrier intended to break up that snowball and allow a more carefully-considered reshaping of some of the snow.Some of the data from the conventional WM measures (counting-, listening-, and digit-span tasks) and the scholastic tests in Experiment 1 were reported by Cowan et al. 1989;60:1239–1249. The highest of these (listening and running spans, r = .58; with age partialled out, counting and running spans correlated higher, rp = .40) again were comparable to the correlations between counting span and listening span (r = .60; rp = .42). 2003;132:113–132. This can be accomplished using a method of analysis described by Chuah and Maybery (1999), based on sets of six stepwise regressions. We thank Jebby Arnold, Ryan Brunner, Troy Johnson, Matt Moreno, and Jennifer Norris for excellent assistance and we thank Moshe Naveh-Benjamin and Jeff Rouder for helpful comments.Performance levels in the visual array task were used to estimate capacity in two ways: in a way described by Pashler (1988) and in another way described briefly by Cowan (2001). New York: Wiley; 1988. Theoretical accounts and applications for scholastic development. The principles of psychology. Without rehearsal, the digit span task should provide an estimate of the scope of attention in young children. 2002;46:153–177. Understanding and measuring intelligence. In: Wilhelm O, Engle RW, editors. Properties of memory for unattended spoken syllables. 1986;38A:675–688. Miller, 1956). Table 3 shows that digit span correlated with ACT scores about as well as did counting span, suggesting that ACT scores are highly weighted toward verbal skill as opposed to general WM ability. Contributions of source and inhibitory mechanisms to age-related retroactive interference in verbal working memory. [PubMed] [Google Scholar]Ruchkin DS, Grafman J, Cameron K, Berndt RS. [PubMed] [Google Scholar]Guttentag RE. An individual-differences analysis. Processing and storage in working memory span. Neural activity predicts individual differences in visual working memory capacity. In: Spence KW, Spence JT, editors. In this case, FA would not be a fair estimate of g.One consequence of the assumption that FA = g is that FA does not always have the intended effect on the estimate of k. There is not yet direct support for either theory.Indirect support for the second theory comes from evidence that the brain representation of attentional control and attentional capacity may differ (see Cowan, 1995). 2. In Experiment 1, we used separate measures of aptitude in adults (high school grade percentiles and the American College Test, or ACT) and children (the Cognitive Abilities Test, or CAT). 2004;50:425–443. The added auditory-sequence-comparison procedure produced capacity estimates in keeping with the expectations of Cowan (2001), averaging between 3 and 4 items in adults and fewer in children. 1998;21:723–802. For example, one practice sentence was "A fox can drive a truck, " requiring the response "no, truck. 1996;7:237–241. Perhaps the ability to carry out a dual task is unrelated to either the theoretical scope of attention or to CAT scores, producing an irrelevant source of variance for storage-and-processing tasks in children.The pattern of means and age effects in this study showed that all of the measures of WM increase with development but that digit span is higher than any other measure at every age group, as shown in Table 1 and Figure 2. Memory development in children. The second experiment provided further refinement; it concentrated on WM tasks modified to be more comparable to one another, and a set of verbal and nonverbal aptitude measures drawn from intelligence tests. Conway et al., 2001; Kane et al., 2001; Kane & Engle, 2003). To distinguish between these two factors, we included an auditory-sequential analogue to the visual-arrays task, using tone sequences. Rate of presentation in running memory and direct manipulation of input-processing strategies. There must be more elementary benefits of attention other than grouping and rehearsal, such as superior encoding of each item. [Google Scholar]Baddeley A. The scope-of-attention measures will be viewed as important even if they do not provide higher correlations with aptitudes than storage-and-processing measures, provided that they pick up much of the common variance of aptitude tasks without as much variance from specific skills that play a role in storage-and-processing spans, but are theoretically distinct from WM (e.g., language comprehension, arithmetic, and counting abilities).We used not only digit span, but also two storage-and-processing measures of WM (listening span and counting span) and four measures of the scope of attention (memory for ignored speech, in Experiment 1; running memory span, in both experiments; visual array comparisons, in both experiments; and a tone-sequence analogue to visual array comparisons, in Experiment 2). The psychology of learning and motivation: Advances in research and theory. First, Tuholski, Engle, and Baylis (2001) found that individual differences in enumeration of a small number of objects in a simultaneous display (i.e., subitizing) were not related to operation span. Current developmental work along these lines suggests that there are limitations in the complexity of concepts that can be represented and understood by children of different developmental levels; specifically, in the number of dimensions of a stimulus display that can be taken into consideration at once (e.g., Andrews & Halford, 2002; Halford, Wilson, & Phillips, 1998). In Experiment 2, the within-age variance in g scores that was uniquely predicted by storage-and-processing tasks (.09) was largely the result of skills specific to listening span and counting span, though there was a residual component shared between them (.03). Spontaneous verbal rehearsal in a memory task as a function of age. Therefore, digit spans do not reliably indicate the scope of attention in these older participants.In sum, we have documented that several measures without a separate processing component, but with impediments to rehearsal and grouping, correlate well with storage-and-processing tasks and with measures of aptitudes in children and adults. After responding "yes" (true) or "no" (false), the participant was to repeat the final word of the sentence and remember it for later. In: Kennedy A, Wilkes A, editors. However, performance on the verbal memory load was 80% to 90% correct in these conditions. [PubMed] [Google Scholar]Conway ARA, Bottoms BL, Nysse KL, Haegerich TM, Davis SL. If sufficient information cannot be retained in WM and integrated, it is assumed that various problems cannot be solved, and that reading or language comprehension cannot be completed. We use the term attention to refer to selective attention, in which some information is selected for processing at the expense of less-than-optimal processing of other information. Todd and Marois (2004) measured fMRI and found that the visual array comparison task caused capacity-limited activity in two small brain areas, the intra-occipital and intra-parietal sulci, during the inter-array period. [Google Scholar]Norman DA. Quarterly Journal of Experimental Psychology. 1990;14:389–433. Some of that shared variance was also shared with digit span (in the prediction of ACT scores), but some of it was not shared with digit span (in the prediction of high school grades, for which digit span was not predictive). [PubMed] [Google Scholar]Luck SJ, Vecera SP. Cowan et al. For that reason, Miller’s magical number seven cannot be taken as evidence that seven separate chunks of information are saved. [Google Scholar]Kail R, Hall LK. (1999) used. There was no significant gain from including separate scope-of-attention and storage-and-processing latent variables (chi-square = 30.38 with df = 22). Other studies have shown dual-task interference even between two tasks differing in modality (Jolicoeur, 1999) and differing in the use of verbal versus nonverbal materials (e.g., Jefferies, Lambon Ralph, & Baddeley, 2004; Morey & Cowan, 2004; Sirevaag, Kramer, Coles, & Donchin, 1989; Stevanovski & Jolicoeur, 2003). First, Mayes (1988) provided evidence that it is reasonable to believe that sensory information can persist for a sufficient duration in this task. Therefore, to determine the use of rehearsal and grouping strategies, one must look beyond the levels of performance, to the correlations between measures.Although some rehearsal may begin at the age of 7 years (e.g., Flavell et al., 1966), rehearsal becomes markedly more cumulative and effective over the next few years, or about through fourth grade (cf. Psychological Bulletin. [Google Scholar]Halford GS, Maybery MT, Bain JD. Verbal and spatial short-term memory: Common sources of developmental change? Children’s working-memory processes: A response-timing analysis. Hove, UK: Psychology Press, Ltd; 1998. Numbers within the overlapping sections of the circles do not represent collinarity between the variables, but portions of ACT variance that are predicted in common by the WM variables shown as overlapping.In keeping with one of our hypotheses, we asked whether the portion of ACT variance uniquely predicted by the storage-and-processing measures (.10) was general or reflected a specific skill. Therefore, only that measure will be reported. Testing was conducted in two sessions, each lasting about 1.5 hours. Values are included only for set sizes in which all participants produced data.Separate 1-way ANOVAs were conducted within each age group on the six measures of WM. [Google Scholar]Daneman M, Hannon B. [Google Scholar]Chen Z. (At the onset of each such series, the four peripheral pictures were named aloud as they appeared on the screen one at a time, as a reminder of the correct labels.) Meanwhile, lists of digits were presented through headphones at a rate of 2 digits per second, at 55 dB(A). 2003;132:93–112. The relationships among working memory, math anxiety, and performance. Thus, there was no consistent advantage for storage-and-processing measures above those measures that do not include a dual task.Experiment 2, Correlations Among MeasuresMeasureDSCSLSRSASVAPPVORMPADigit Span (DS)0.890.540.680.700.500.310.640.630.480.45Counting Span (CS)0.47*0.870.700.650.500.430.570.540.720.62Listening Span (LS)0.60*0.60*0.860.670.510.570.780.780.660.50Running Span (RS)0.63*0.57*0.58*0.890.440.500.590.590.580.54Auditory Sequences (AS)0.45*0.44*0.45*0.40*0.910.400.420.350.470.37Visual Arrays (VA)0.28*0.38*0.51*0.45*0.36*0.910.500.500.530.44PPVT (PP)0.59*0.51*0.70*0.54*0.39*0.47*0.950.920.730.65S-B Vocabulary (VO)0.56*0.48*0.68*0.52*0.32*0.46*0.85*0.900.660.61Ravens (RM)0.42*0.63*0.58*0.51*0.42*0.48*0.67*0.59*0.880.75S-B Pattern Analysis (PA)0.41*0.56*0.45*0.49*0.34*0.41*0.61*0.56*0.68*0.93Experiment 2, Correlations Among Measures With Age Group Partialled OutMeasureDSCSLSRSASVAPPVORMPADigit Span (DS)0.890.360.510.560.430.080.380.370.260.17Counting Span (CS)0.27*0.870.570.510.430.270.320.280.620.46Listening Span (LS)0.37*0.42*0.860.460.450.410.560.560.490.19Running Span (RS)0.44*0.40*0.32*0.890.370.320.230.230.380.29Auditory Sequences (AS)0.37*0.37*0.37*0.31*0.910.320.360.240.400.27Visual Arrays (VA)0.040.21*0.32*0.25*0.28*0.910.260.270.390.25PPVT (PP)0.28*0.22*0.39*0.130.31*0.20*0.950.780.600.36S-B Vocabulary (VO)0.24*0.160.36*0.100.18*0.18*0.57*0.900.460.29Ravens (RM)0.18*0.50*0.36*0.28*0.34*0.31*0.47*0.31*0.880.64S-B Pattern Analysis (PA)0.110.37*0.100.21*0.23*0.20*0.27*0.19*0.54*0.93Another way to judge the validity of WM measures is to examine the profile of its correlations. Instead, the critical point may be that the processing task prevents continual rehearsal and grouping of the information to be stored during the stimulus presentation. In: Bower G, editor. 135–182. A priori, a key consideration is that the ability to carry out computations and mental manipulations of various sorts could be dependent on the ability to hold in mind the data while it is processed (for relevant work see Logie & Gilhooly, 1998). Psychology & Aging. The individual differences in electrical activity (measured as the change in activity between trials with 2 vs. They were to make a single key press indicating whether that square had changed or whether there had been no change.On each trial, which was initiated by the participant when ready, a fixation cross was presented for 1 s and was followed by a presentation of the first array of squares for 250 ms. If either of these possibilities is true, there should be a strong relation between attentional control and the measured scope of attention. This expectation was met resoundingly. The activity increased as a function of array size only up to a limit of 3 to 4 items, which again matched the behavioral limit.

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