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DE RIBAUPIERRE, Anik


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Working memory and individual differences: A review
Anik de Ribaupierre
FPSE, University of Geneva

The objective of this paper is to review studies on individual differences in two areas of working memory research, namely studies derived from Baddeley's model and neo-piagetian studies. The two types of models are first briefly summarized. Three lines of work are then reviewed: (1) studies which have addressed the issue of intra-individual or between-group differences, among which Della Sala et al.'s study is described in more detail; (2) studies which have focused on the relationship between working memory and other cognitive domains, either through comparison of special groups or by means of correlational analyses; and (3) studies which have addressed the generality versus specificity of processes involved in working memory. The conclusion draws attention to the necessity of conducting more analyses of qualitative versus quantitative individual differences, using Reuchlin's model of vicarious processes.

The area of working memory is so vast that an extensive review would be impossible, even when restricted to the issue of individual differences. This paper will focus on two types of approaches which have not only proposed a model of functioning of WM, but have also made suggestions about its implications for cognitive development. These are studies derived from Baddeley's model and the neo-piagetian approaches. A large part of this article will be devoted to studies inspired by Baddeley's model, which is a predominant reference in this area, and to studies on adult cognition. Taking into account the origins of my interest in this problem, as well as the importance granted to the concept of working memory (WM) in developmental psychology, it is nevertheless interesting to try to establish a parallel between experimental studies with adults, on the one hand, and developmental studies, in particular neo-piagetian models, on the other hand.

The objective of this paper is therefore to draw the attention to the possibility of approaching these two types of models, which at first sight seem rather incompatible and to give an overview of research on individual differences. Like in other areas, the differential approach in this domain can be understood in several ways. First of all, differentials (i.e., researchers interested in individual differences) may attempt to evaluate the working memory capacity of individuals, usually with predictive, often applied aims. It is undoubtedly for this reason that most intelligence scales include at least one test of short term memory (STM). Most recent studies within this perspective have dealt with the relationship between WM and verbal comprehension. Testing to what extent WM or STM tasks help predict cognitive performance in other tasks is by far the direction most frequently taken by researchers interested in individual differences.

Differentialists may also grant a fundamental importance to the issue of intra-individual variability, asking whether performances are homogeneous or vary greatly across different WM tasks, and hence whether similar processes are at work in various WM tests. This question has been addressed by means of correlational and factorial methods, and more recently of confirmatory factorial analyses and models of structural equations. Studies of this type are relatively recent in the field of working memory, and they have usually been combined with the preceding question of the relationship between memory and other cognitive functions. Another issue of interest has been the degree of overlap between a possible general memory factor and a general intelligence factor.

There has been a tendency to forget, at least among generalists, that individual differences do not merely constitute quantitative variations around a general norm but that they also serve to test the validity of general laws. The issue raised is whether all individuals function similarly. This question is particularly relevant in the WM area since many models have been inspired by cognitive neuropsychology. Examining patients with selective deficits, using a paradigm of double dissociation, has generated a large amount of information about the functioning of WM. Very few studies have attempted, however, to uncover such dissociations in so-called "normal" individuals. On the contrary, the implicit postulate has often been that all those subjects who do suffer from a pathological deficit should function in the same way. Our hypothesis is that dissociations, or double dissociations, also exist in "normal" subjects.

The remainder of this paper is organized as follows. In the first section, Baddeley's model is briefly presented, as well as overall results obtained in studies with children and adults; the neo-piagetian approaches are then shortly summarized. The second section deals with the issue of between-group differences. The third section refers to individual or between-group differences, but is specifically concerned with studies that have investigated the relationship between WM and other cognitive variables. It should be remarked that, strictly speaking, this type of studies does not center on differences in the functioning of WM per se, but rather on individual differences in the variable of interest, considered as the dependent variable. The question asked is, for instance, whether individual differences in reading can be accounted for by individual differences in WM. Interestingly enough, it is nevertheless this perspective, and only this one, that is usually referred to in reviews on individual differences in WM (Baddeley, 1992a; Ehrlich & Delafos, 1990). An exhaustive review of this area is impossible; we will essentially rely on the Daneman & Carpenter studies and some of the neo-piagetian studies. The fourth section focuses on intra-individual variability and presents the results of studies that have used an important number of memory tests, in contrast with the preceding ones. Finally, the conclusion emphasizes the need for studies relating inter- and intra-individual variability, using the model of vicarances suggested by Reuchlin (1978) and Pascual-Leone's model.

The Concept of Working Memory

The concept of WM evolved from that of STM. This term was suggested by Baddeley & Hitch in 1974, for two reasons. On the one hand, they meant to insist on the fact that STM can function as a working space, that is, a system that can both temporarily maintain information and process it for use in numerous other cognitive tasks, such as reasoning, comprehension, and learning. On the other hand, they wanted to demarcate WM from STM, usually considered as presenting a unitary character.

Before describing Baddeley's model, a number of remarks appear in order. It should be stressed that the concept of WM is not unanimously defined. Whereas there seems to be a consensus as to three levels of processing as proposed by Atkinson & Shiffrin (1968) — sensory registers, temporary and long term storage of information —, the difference between WM and STM and the extent to which the WM system is still controversial. In developmental psychology in particular, WM and STM are still used as interchangeable terms (cf Dempster, 1980, 1985). The distinction appears somewhat clearer at the level of the tasks used. WM tasks usually embody a dual task paradigm, as in most of Baddeley's studies, or call for both storage and processing, like the reading span task proposed by Daneman & Carpenter. In contrast, STM tasks refer to situations that require only storage. A number of authors nevertheless use the term STM for every task that demands a more or less immediate retrieval of the material to be memorized; this would include WM tasks. Halfford (1993) also stresses the lack of consensus in the domain, and points to the large number of approaches and definitions, such as the concepts of resources, capacity, short term memory span, working memo-
ry, total processing space, primary memory, M-space, processing speed. Part of the confusion results, we believe, from a frequent confounding between the tasks and the processes at work.

There are clearly two classes of models of WM. For certain researchers, probably including Baddeley, WM is a system with its own specific processes, in the sense of memory systems theorists (e.g., Schaeter & Tulving, 1994). For others, WM is simply a highly activated subset of long term memory. In the latter case, the capacity of WM is defined by its content, and the processes involved in a WM task are the same as those involved in many other cognitive tasks; only their relative contribution changes across different types of tasks. This is the case of Pascual-Leone's model, for example, as will be discussed later in this paper. Moscovitch (1992) also argues that WM is not to be considered as a specific system, but corresponds to a set of schemes activated in an attentional manner; for instance Moscovitch & Umilta (1990, p. 31) write: "A more plausible solution is that there is neither a single WM system in Baddeley's sense nor are there multiple WM systems. Instead, WM is the entity that reflects or represents whatever processes are currently active and whose outcomes or operations are consciously apprehended... the capacity of WM will vary depending on which central (and sometimes modular) process is currently active, not because there are multiple WM systems but because multiple processes and their output are capable of capturing and occupying our attention (and conscious awareness)." Other authors, too, view WM as a strongly activated subset of long term memory (e.g., Cantor & Engle, 1993; Cowan, 1993; Engle, Cantor & Carullo, 1992; Salthouse, 1990). The number of components, processes and/or modules proposed differ widely from one author to another.

**Baddeley's Working Memory model**

Baddeley & Hitch (1974) proposed a multiple component model, which has only been slightly revised over the last twenty years (Baddeley, 1986, 1990; see also Ehrlich & Delafey, 1990). WM is composed of at least three modules: a central executive (CE) and two slave systems that can function independently from one another, the phonological loop (PL) and the visuo-spatial sketchpad (VSSP). The more clearly defined component is the phonological loop, whereas the other two remain somewhat unknown, and are often defined for what they do not do: The VSSP monitors visual and spatial information as opposed to verbal information and is not interfered with by tasks that involve the PL, the central executive is supposed to operate in complex tasks, accounting for effects other than those due to the slave systems.

The central executive is described as a regulatory device. It coordinates the different activities that take place in WM, controls the transmission of information among different parts of the cognitive system, monitors the functioning and coordination of the slave systems and retrieves information from long term memory. Its resources are limited. Although Baddeley recognizes that it is a system that we still hardly know, he refers to the model of attentional control proposed by Norman & Shallice, suggesting that the central executive activities are situated in the frontal lobe; an injury at this level would generate a dysexecutive syndrome. The CE has been defined mainly by what it does not do and has rarely been studied on its own, certain tasks of WM are supposed to address it more directly (Baddeley, 1992b). These are either coordination tasks (coordinate two simple tasks, one involving the PL and the other involving the VSSP), or tasks in which the subjects are asked to generate random digit or letter sequences, with the aim of inhibiting automatic routines (e.g., sequences of letters in alphabetical order). It is also interesting to note that the Reading Span task from Daneman & Carpenter, which will be analyzed later in this article, is considered by Baddeley as a CE measure (Gathercole & Baddeley, 1993) and not only a PL task.

The PL maintains and processes verbal information. It is composed of a register, or phonological store unit, containing verbal information that can either disappear with time, or be refreshed and rehearsed by a subvocal or articulatory rehearsal mechanism. The hypothesis is that verbal material presented in an auditory modality directly enters the phonological store unit, and might be refreshed by the subvocal or phonological rehearsal mechanism. Verbal material presented in a visual modality (word or image) will instead be first recorded phonologically by this mechanism, and then stocked in the phonological register where it can be refreshed by the same means. The PL is considered to be temporally limited. It can retain the number of items which can be repeated in approximately two seconds. The hypotheses regarding the phonological loop account for a number of empirical phenomena, such as the articulatory suppression effect, the phonological similarity effect, the word length effect, and the unattended speech effect (for details, see Baddeley, 1986).

The role of the VSSP is to process and retain visual and spatial information, as well as verbal information that will later be stored as images. According to recent studies, it seems the VSSP has a visual and a spatial component (e.g., Baddeley, 1988; Buech, 1984; Logie, 1995; Logie & Marchetti, 1991). The number of studies dealing with this component has greatly increased in the last ten years; however, its capacity and the mechanisms used for maintenance and rehearsal remain largely unknown (e.g., Monnier & Roulin, 1990). Baddeley's model has inspired many empirical studies. In the developmental perspective which is of more interest here insofar as we will also discuss neo- Piagetian models, a majority of studies have tried to determine whether the same effects are obtained in children. Hitch et al. (1988, 1989a; Hitch, Woodin & Baker, 1989), for instance, demonstrated that the relative importance of the phonological loop increases with age, even though its effects are already observed in pre-school children. For auditory stimuli, the word length effect and the phonological similarity effect are observed very early. In contrast, the same effects are not observed in children under 7 for visually presented stimuli (image presentation). The work of Hitch tends to demonstrate that developmental change does not merely consist in a transition from a visual code to a phonological one, but corresponds rather to an increase in flexibility of usage of the different codes.

It is well known that memory span increases with age, even though this increase is not very large (Dempster, 1985). For Baddeley (1986), this increase is essentially due to an increase in articulatory speed (or rhythm of subvocal rehearsal). Several studies demonstrated a linear relation between span and articulatory speed (Hulme et al., 1984; Hulme & Tordoff, 1989; Nicolson, 1981) or identification speed (Case, Kurland & Goldberg, 1982). However, other recent studies (Halliday & Hitch, 1988; Henry, 1991a, 1991b, 1994; Henry & Millar, 1993) showed that age differences do not totally disappear when differences in articulatory speed are controlled for; some age effects also persist under articulatory suppression. This shows that the development of span cannot be entirely assigned to an increase of articulatory speed. In contrast, few studies have focused on age changes in the VSSP. Wilson, Scott & Power (1987) observed an increase in performance in a spatial span task (memorizing a sequence of positions that can be encoded as patterns). Monnier (1994) also obtained age effects in patterns span, although they were not very large. Schumann-Hengsteler (1992; Schumann-Hengsteler, Demmel & Seitz, 1992) found very little change between 5 and 10 years in recall for positions.

Not directly addressed is the issue of a developmental change in the CE. An increase with age can certainly be hypothesized, however, both with respect to its capacity and to its efficiency. This hypothesis is advanced here on several grounds. First, the large number of studies that were conducted on the development of strategies with age; such changes in strategies almost certainly will influence the efficiency of the CE as a regulating system. Second, a certain number of authors have emphasized the importance of a mechanism of inhibition in development (e.g., Bjorklund & Harnischfeger, 1990; Dempster, 1991), which is most probably involved in the CE. Finally, changes with age have been reported in tasks such as the Reading and Listening Span, which are considered by Baddeley to involve the CE.
The neo-piagetian models that deal with the issue of WM have a completely different origin. Derived from the piagetian model, they replace the piagetian "structure d'ensemble" by other constructs in order to account for general stages of development. The general stages are now defined in terms of upper limits in the performances that can be attained, rather than by the form of behavior across situations; this is more compatible with the large variability observed in cognitive performance. These upper limits are constrained by the size of working memory or attentional capacity. Not all neo-piagetian models address WM, and different constructs have been used, just like in mainstream experimental psychology (e.g., Case, 1985, 1992; Chapman, 1987; Fischer & Silvern, 1985; Halford, 1987, 1993; Halford et al., 1994; Pascual-Leone, 1970, 1987). This paper will mainly refer to Pascual-Leone's model, which attempts to account simultaneously for developmental and for different aspects. Case's model will, however, also be briefly mentioned, so much more so as certain studies based on Baddeley's perspective refer to it explicitly (e.g., Baddeley, 1986; Hitch et al., 1989b; Hitch & Towse, in press).

The role assigned to WM in neo-piagetian models is one of retention and information processing, similar to the one it has in Baddeley's approach. Case (1985), for instance, explicitly postulates a trade off between retention and processing; more efficient the processing (due for example to practice), the more retention space will be left.

Pascual-Leone's model is a rather complex one. Let us first stress that this model has often been erroneously considered to view WM as a unitary system (see for example Baddeley, 1986; Halford, 1993). On the contrary, Pascual-Leone's model is fundamentally multidimensional, whether with respect to WM or cognitive development in general. It is not easy to establish a correspondence between Baddeley's and Pascual-Leone's definitions of WM, but a rapprochement can be made (see de Ribau-pierre & Bailleux, 1994). In Pascual-Leone's model, WM corresponds to a set of highly activated schemes which concur to the performance in a given task. It is therefore not to be considered as a system, but rather, similar with Moscovitch's propositions (see above), as a conglomerate of currently activated units of information. Activation is described as a three-phase process (Pascual-Leone, 1984; Pascual-Leone & Baillargeron, 1994; Pascual-Leone & Ijaz, 1989). When an input is processed, a relatively large set of schemes is first activated, somewhat automatically; together these schemes constitute the "activation field". Executive schemes, as well as a number of mechanisms or silent operators are then mobilized and a subset of schemes is more highly activated. It is probably this subset that corresponds most closely to Baddeley's concept of WM. Finally, depending on the type of situations, certain schemes are inhibited while others are even more strongly activated. This last subset of hyper-activated schemes defines, according to Pascual-Leone, the field of mental attention. Three mechanisms contribute to the selection and activation of schemes in the field of mental attention: a) M power, which boosts the weight of schemes which are relevant to the situation and are not directly activated by the stimulus or by other operators; b) an inhibition mechanism responsible for lowering the weight of irrelevant, often highly activated schemes and c) executive schemes which are responsible for the control of performance, in particular planning and monitoring, and for the attribution of resources. These three mechanisms together play a role comparable, we believe, to that assigned to the central executive in Baddeley's model. Note that, in this case, Pascual-Leone hypothesizes that several processes are at play; in contrast, Baddeley does not decompose further the CE, although he acknowledges this as a possibility (Baddeley, 1992b, 1993).

Pascual-Leone has made precise developmental predictions about the capacity of M power, defined as the number of schemes that can be simultaneously boosted in a single operation; it ranges from one scheme at age 3 to seven schemes at age 15. This increase defines stages that have been empirically determined to last two years. Although the concept of M operator has generated the most empirical studies, it is not the only mechanism considered by the model to explain developmental changes in performances; a number of other processes are seen to account for individual differences as well as for developmental differences.

**Inter-individual and/or inter-group differences in the functioning of Working Memory**

Although Baddeley's model was not meant to deal with interindividual or intergroup differences, it is interesting to note first that it was partly elaborated on the basis of data obtained from contrasted groups of subjects. This is shown by the place given to cognitive neuropsychological studies in the construction of the model (e.g., Baddeley, 1986; Gathercole & Baddeley, 1993). It is because different patterns were observed in different types of patients (double dissociation paradigm) that several components were postulated. For instance, Baddeley compared amnesic patients and subjects with a short-term memory deficiency, showing that the latter were nevertheless capable of making long-term acquisitions. The definition of the two components of the PL was also validated by case studies; for instance, certain patients showed a deficit of the phonological register while still presenting the effects expected from a correct functioning of the rehearsal mechanism. Results from one patient (Val- lar & Baddeley, 1984), in contrast, attested to a deficiency of the rehearsal mechanism with a preserved phonological register. Finally, the fact that dysarthric patients function similarly to normal subjects led Baddeley to conclude that the articulatory rehearsal mechanism was not connected to peripheral mechanisms of language. However, this is a particular way of using individual differences, for it serves to validate hypotheses related to general mechanisms; indeed, it consists in focusing on the consequences of the dysfunction of a component which is in fact considered to be universal. In our opinion, Della Sala et al. (1991) adopted an approach which is exemplary as concerns the study of individual differences; this is why their study is reported in some detail. They were primarily interested in the relationship between articulatory rehearsal and short-term verbal memory in dysarthric or anaphoric patients. They first compared the results of five anaphoric patients described in several studies by others (e.g., Gathercole & Baddeley, 1993). This amounts to studying inter-individual differences within a sample of patients. They observed that the patients were not homogeneous, even though suffering from the same disorder (albeit arising from different etiologies): They were all sensitive to the phonological similarity effect in an auditory condition, which demonstrates that their phonological register functions more or less correctly. Only four of them, however, presented the same effect in a visual condition. Furthermore, the word length effect was observed in only two of the five patients in an auditory condition and in only two of the three patients studied in a visual condition. This led the authors to accept Cubelli & Nichelli's suggestions (in Della Sala et al., 1991) that articulatory coding has to be dissociated from articulatory rehearsal, resulting in the introduction of a third component in the PL. The role of articulatory coding would be to translate visual information in a phonological code, whereas this translation was assigned to the rehearsal mechanisms in the original model. Once translated, information would be directly transferred to the storage unit, allowing for its rehearsal. A deficit in articulatory coding would be compatible with a word length effect (adequate functioning of the rehearsal mechanism) and a phonological effect in auditory presentation (direct access to the storage unit and its adequate functioning); none of these effects would be observed in visual presentation. Conversely, other patients might present a selective deficit of articulatory rehearsal but not of articulatory coding; in this case, a phonological effect should be observed both in a visual (phonological translation by the new module) and in an auditory presentation (direct access to the storage unit), but a word length effect should be found only in visual presentation (due to phonological recording which takes more time for long words). These conclusions lead therefore to a slight modification of the model, on the basis of individual differences within a group of patients that were supposed to be homogeneous at the beginning of the study.

Furhering the study of one of the anaphoric patients, Della Sala et al. remarked that, this
time, the control patient did not show the expected effects (no phonological-similarity effect). They suggested the as yet unforeseen possibility that not all subjects function in the same way. To test this hypothesis, they proposed a series of tasks to fifteen control subjects, some of which apparently failed to show the expected pattern across situations. Considering that this could be due to a relative insensitivity of the measure, the authors conducted a still more detailed study on two of these subjects; one of them even presented a superior recall for long words, which is a reverse word length effect, possibly due to the use of mnemonic strategies. Although their results are not really conclusive since they were obtained on a very restricted number of subjects, they tend to support our hypothesis, according to which different subjects may function differently in WM tasks.

Other studies were interested in individual differences in special groups. For instance, Hulme & Mackenzie (1992) studied verbal recall in severely mentally retarded subjects (IQ equal to or less than 50). They compared three groups of 55 subjects each, matched in mental age (mean mental age 6 years): Down syndrome, varied etiologies with chronological ages between 12–13 years, and control children of 6 years of chronological age. The mentally retarded subjects were significantly inferior to the control children, in a digit span task; this shows that their degree of retardation was even higher in the digit span task than in the vocabulary test that was used to establish mental age. In addition, the correlation between mental age and memory span was significantly higher in the control children (r=.71) than in the other two groups (.41 and .43 respectively). A longitudinal follow-up of the sample showed that the retarded subjects develop more slowly in terms of their memory span than in terms of mental age. Two years later, a significant increase in mental age was observed, but not in span. Five years after the first assessment, memory span had significantly progressed but remained inferior to expectations based on mental age. In contrast, the control children showed a considerable progress both in memory span and mental age, and their results on the digit span task remained conform to the norms for their age. Results point therefore to an increasing deviation between mental age and memory span. Hulme & Mackenzie also studied in more detail the phonological loop system. As expected, word length was related to articulatory rate in all groups (more short words than long words repeated per second); however, word length was not related to recall in retarded subjects. Furthermore, the slope of the regression line linking articulatory rate and recall as a function of word length was flatter for them than for the controls. The authors suggest that the specific deficit shown by the retarded subjects in the digit span test is essentially due to a deficit in the rehearsal process. The retarded subjects were also less sensitive to the phonological similarity effect, which the authors attribute to the rehearsal process. This hypothesis was strengthened in an ultralow study, conducted with retarded adolescents, in which they showed that learning a rehearsal strategy leads to an increase in memory span, as well as to a larger phonological similarity effect.

Few studies have been conducted in a neo-piagetian context on the importance of individual differences. In this context, the focus has mainly been on comparing attentional capacity of WM among different age groups, in order to validate developmental hypotheses. WM or attentional capacity is postulated to impose a general ceiling on cognitive performances, which does not preclude a strong situational and individual variability underneath these limits (e.g., Fischer & Silvern, 1985). However, this variability was mostly emphasized in other cognitive tasks. As regards more specifically WM tasks, neo-piagetian models usually postulate only quantitative individual differences, corresponding to different developmental speeds for different types of children. However, they also hypothesize that these differences (such as related to social class for instance) should be less important than in other, complex cognitive tasks. Indeed, most empirical studies carried out in this context have dealt with the universality of the M operator. For instance, Globerson (1983) showed that social class differences were almost non-existent in the neo-piagetian WM tasks, whereas they were much larger in other cognitive tasks. The gap between social classes increased as a function of the increasing importance of the executive schemes or more complex performance strategies. In the same vein, Miller et al. (Miller, Bentley & Pascaul-Leone, 1989; Miller et al., 1989) suggested that M capacity tasks are less sensitive to cultural differences; they demonstrated that black children form South Africa attained performances comparable to those of white middle-class Canadian children. Dassen & de Ribaupierre (1987) discuss in more detail the importance given by the neo-piagetian models to interindividual and intercultural differences.

Relationship between WM and Cognitive Performances

As already mentioned, it is usually this category of studies which is mentioned when addressing the issue of interindividual differences in WM (e.g., Baddeley, 1992b). Based on the hypothesis that STM is a working space used in numerous cognitive situations, the question asked here is whether individual differences in WM tasks are related to, or permit the prediction of, individual differences in other types of task. A large part of the studies mentioned here deal with reading, which is partly surprising since the focus has mainly been placed on verbal memory tasks. The issue can be addressed in two ways: either comparing groups of subjects, generally on the basis of a deficit or dysfunction, or adopting a correlational approach. Only a few examples of each approach are given below.

Group Comparison

A number of studies concerns the comparison of skilled and disabled readers. For instance Siegel (e.g., Siegel & Linder, 1984; Siegel & Ryan, 1988, 1989), showed that reading disabled children have worse performances in STM and WM tests than normal readers. In particular she demonstrated that reading disabled children had difficulties in verbal (Listening span) and numerical (Counting span) WM tasks. In contrast, arithmetic disabled children only experienced difficulties in the Counting Span task. Siegel suggests therefore to distinguish several types of WM. Hitch & McAuley (1991) confirmed the fact that arithmetic disabled children have difficulties in a WM task when the concurrent task consists in counting operations, either in visual or auditory presentation. However, they propose that the deficit is essentially due to a deficit in basic components such as digit retention and counting speed, rather than a deficit in WM per se; the hypothesis of different, specific WM systems would therefore be superfluous. In another study, probably unique by its breadth in terms of age range, Siegel (1994) administered a WM test (Listening Span) and a STM test (letter recall) to subjects between 6 and 49 years; differences observed between skilled and disabled readers were again found at all ages.

Swanson (1993) also observed that learning disabled readers from grades 6 and 7 obtained lower scores in WM measures than skilled readers; this difference was not observed in STM tasks. However, he also noted that the relationship between WM and reading was higher in average readers than in skilled or learning disabled readers.

Gathercole & Baddeley (1990, 1993) propose that language disordered children present a specific deficit of the phonological WM system, which cannot be explained on the basis of their poor linguistic skills alone, but seems to arise from a limited or poorly functioning phonological register. In the context of Case's neo-piagetian model, Porath (1992) compared three groups of gifted children (total IQ, verbal IQ or performance IQ over 130) to children matched in terms of chronological or of mental age. As expected, the gifted children scored higher in their domain of excellence (e.g., in narration or in drawing tasks) than chronologically matched children; however, there was no difference in WM tests. Crummond (1992) administered a visuospatial and a verbal WM task to three groups of learning disabled children (difficulties in reading, mathematics or both). Their scores were lower than those of children of the
same chronological age. In addition, they did not show a larger between-task discrepancy; in deed, one could have expected that reading dis abled children, for instance, experience more difficulties in the verbal than in the visuospatial span task. This was not observed. On the basis of these two studies, it can be speculated that learning disability is related to a delay in the development of attentional capacity or WM, whereas giftedness (as defined by IQ tests) results from a more advanced knowledge base and better strategies, rather than from an advance in the development of attentional capacity. Shire (1990) also found a difference in an attentional capacity task between good and poor students. However, this difference was smaller than the one observed in a piagetian test of conservation.

**Correlation between WM and cognitive performance**

Another issue addressed by researchers interested in individual differences was that of the correlation between WM tasks and other cognitive tasks. A considerable number of studies examined the relationship between WM and verbal comprehension or reading, following Daneman & Carpenter’s (1980) seminal study. These authors adopted a definition of WM similar to Case’s, and proposed a measure, the Reading Span test, inspired by Case’s Counting Span (Case et al., 1982). In this task, subjects are asked to process a series of sentences and to retain the last word of each sentence. The task is generally presented as a classic span task, in which the number of sentences in the series is progressively increased and the test is stopped after a certain number of failures. Daneman & Carpenter showed that, even in samples of college students (i.e., samples with reduced variance), the memory span of skilled readers was superior to that of less skilled readers. Numerous versions of this task have been used since (e.g., Daneman & Merikle, 1994), which vary the mode of presentation and the conditions of sentence processing (e.g., processing the sentence explicitly versus simply reading it, forced choice versus answering questions, etc.). Typically, the correlations obtained between the Reading Span and general reading scores like the Scholastic Achievement Test (SAT) range from 0.50 to 0.60; they are even higher with more specific psycholinguistic tests like anaphoric reference, search for incoherence, or prose memory (see Baddeley et al., 1985; Baker, 1985; Daneman & Carpenter, 1980, 1983; Daneman, Carpenter, & Just, 1982). Carpenter & Just (e.g., Carpenter & Just, 1989; Just & Carpenter, 1992) focused on underlying processes in the Reading Span task, comparing eye movements patterns in high and low memory span subjects. High span subjects read the sentences faster; this suggests that the lexical access is faster in these subjects, allowing them more time to study the final words. Changes in strategy were also observed in high span subjects, but not in low span subjects, with an increase in memory load; they spent less time reading the sentences in longer series than in shorter series, again suggesting that they attributed more resources to maintenance and rehearsal. The authors also showed a relation between lexical and syntactic difficulty, on the one hand, and memory span, on the other hand: the difficulty of the sentences interfered with recall only at span level. Low memory span subjects were already disturbed by lexical or syntactic difficulty in two sentence series, whereas high memory span subjects were disturbed only by the four sentence series. The authors conclude to two types of systematic individual differences: memory span differences per se, and differences in resource monitoring which would be more dynamic in high span subjects.

Daneman & Carpenter (e.g., 1980) systematically insisted on the necessity to define WM in terms of operational capacity, WM being not only a retention or storage capacity, but a processing, operating capacity as well. Their hypothesis is that WM is specific to a group of processes in a particular domain. High correlations may arise from the fact that the same processes are involved in the reading span task and in reading activities. Because they are less efficient in reading, poor readers (or less skilled readers, considering that most subjects were college students) must allocate more resources to processing the sentences and thus dispose of fewer resources to encode and maintain information in WM. However, the hypothesis can be reversed: Because they would dispose of fewer resources in general, or of a lower WM capacity, certain subjects would be less efficient readers. This is the hypothesis adopted by Engle in particular (e.g., Conway & Engle, 1994; Turner & Engle, 1989; Engle et al., 1990, 1992), who showed that correlations are just as high between a task called Operation Span (in which subjects have to verify if a mathemati
cal operation is correct while maintaining either a word – operations-word task – present ed after the operation, or the last digit) and reading, on the one hand, as between the Reading Span test and reading, on the other hand. Checking the answer to the operation evidently calls for other processes than sentence comprehension or reading; the correlation obtained between the WM task and reading cannot be explained in terms of specific processes. The authors consider therefore that WM is a general capacity, independent of reading. Comparing STM and WM tasks, they write (Engle et al., 1992, p. 991): “The WM variable is important in comprehension because of the retention of surface-level codes, such as the exact words of a recent clause or phrase [that is, for surface coding] The working memory variable is important in building the mental model or gist of the developing story.” In the same vein, Swanson also contrasted STM and WM tasks according to their respective contribution to reading and concluded to the greater generality of WM tasks. Although some positive correlations were found between STM and comprehension, correlations were higher for WM tasks; furthermore, he found that the “learning disabled children’s WM problems are not isolated to reading. Instead, the results suggest that LD children’s memory problems cut across different academic and aptitude domains, suggesting that their problems in processing information are functionally related to higher order processes, such as central executive processing” (Swanson, 1993, p. 328).

Other studies have also shown that there is a relation between verbal WM and language activities. For example, Gathercole & Baddeley (1993) showed that phonological memory (nonword rehearsal) at 4 years of age was a good predictor of long-term vocabulary acquisition. Service & Rastas (1992) showed that phonological memory was a good predictor for second language acquisition. Hulme (1988, cited in Hulme & Mackenize, 1992) has also found significant correlations between memory span and reading in 7- to 10-year-old children, even when the effects of age, IQ and verbal comprehension were controlled.

Mukunda & Hall (1992) conducted metaanalyses on the relationship between memory tests and general aptitude measures, based on an important number of studies. They were interested a) in possible changes in the relationship with age, b) in the distinction between aptitude and achievement tests and c) in the difference between complex tests, like the Reading Span, and simple span tests as concerns their relationship with aptitude measures. Only studies of serial recall with sequential presentation were included. The mean correlation obtained between memory tests (all tests together) and cognitive tests was .248; the authors stress a large between-task and/or between-study variability in the correlations. In conformity with their hypothesis, complex WM tasks (i.e., tasks which demand both processing and recall) presented higher correlations than simple span tasks, but this difference was more marked with respect to achievement tests. The authors also propose a certain number of “quality” or reliability criteria (number of trials, administration of the entire task versus a classical span procedure, automatized presentation). Effects were considerably stronger when the quality of the test was higher; the mean correlation between WM tests and achievement tests increased from .335 to .420 when tests were weighted by this quality criterion. Age had no influence on this effect, which tends to imply that relations between memory and scores in psychometric cognitive tests remain constant throughout the different age ranges. On the one hand, this lack of difference might seem surprising, for one could expect that the relative part of other variables (such as an increase in the knowledge base) would differ with age, resulting in a lowered correlation of WM and cognitive tasks. It may be related to the definition of the age groups: five groups were defined for the period between preschool age and adolescence and only one group for adults. On the other hand, however, this result is congruent
with the studies described above, in which relationships between WM and cognitive performances were observed even within samples of adults who are relatively homogenous in terms of their cognitive level.

Neo-piagetians have posited a relation of implication, rather than one of correlation, between WM and performance in cognitive performance. The hypothesis is that, because of the ceiling imposed by attentional capacity, a subject cannot attain a given level of performance before having reached a sufficient level in terms of attentional resources (this level being defined on the basis of a theoretical analysis of the task complexity). It is, however, quite possible that subjects function below the level corresponding to their resources. A number of empirical studies were conducted to test this relation, and showed that scores on attentional capacity tasks successfully predict performance on a whole range of tasks, representative of many domains, such as piagetian tasks, language, metrical judgment (for more details, see Case, 1987, 1992; Chapman, 1987; Chapman & Lindenberger, 1989; de Ribau-pierre, 1983; Stewart & Pascual-Leone, 1992). Case has also conducted several training experiments, showing that progress was only obtained in subjects presenting the required WM level (Case, 1985).

**Working Memory: one or several dimensions?**

The question raised here is that of the generality versus specificity of working memory. This question has generally been addressed via the study of intra-individual variability, by means of correlational or factorial methods. It is not always easy to differentiate this approach from the one described in the preceding section, since both use a correlational method. The particularity of the studies mentioned here is that they questioned the relationship among various tests of WM rather than between WM and other cognitive performances; therefore a number of different memory tests were used with the same subjects. However, most authors questioning the unidimensionality of WM also used other cognitive tests and therefore addressed the relationship between WM and other areas. Likewise, authors who used only one or two WM tests tend nevertheless to draw conclusions about the general nature of the processes. It was mentioned above that, for Daneman & Carpentier for instance, WM such as evaluated in the Reading Span does not reflect a general process, but activates specific processes common to reading and WM tests. On the contrary, for other authors, including neo-piagetians, WM involves general processes operating in a whole range of situations. For instance, as was mentioned above, Turner & Engle (1989; see also Engle, Nations & Cantor, 1990; Engle et al., 1992) suggest that individual differences in WM capacity reflect differences of a general nature, which should show in a number of different tasks. In contrast with Daneman’s approach, for instance, their conclusions are also backed up by studies involving a larger number of tasks, and using factor analyses contrasting WM and STM tasks. Likewise, Swanson (1993) resorts to hierarchical and confirmatory factor analyses to show that WM tasks tend to group on a same factor, different from STM tasks.

There are few studies which used a sufficiently high number of tasks, to test this question. The very large scale used by Kylonen & Crystal (1990) is a good example of this type of approach. Their hypothesis was that WM capacity represents a central, albeit not the only one, factor of cognitive functioning; the other factors would be processing speed, declarative knowledge and procedural knowledge. The test battery included psychometric and laboratory tests and was administered to more than 2000 recruits of the American air force over several studies. Using confirmatory factor analyses, the authors demonstrated the existence of a general WM factor in each study. They concluded that WM capacity is a general process, relatively independent from its content. It has to be stressed that the memory tasks were either verbal or numerical, but that there were no visuospatial task. It should also be noted that correlations were equally strong between the memory factor and the reasoning factor (around .80). However, these two factors cannot be completely superimposed: The reasoning factor correlated more strongly with a general knowledge factor, whereas the WM factor correlated more highly with a perceptual speed factor.

Miller & Vernon (1992) also found a general memory factor. They used a large battery of tests subdivided into three categories: verbal and visuospatial memory tests, group intelligence tests and processing speed tests, some of which also rely on STM. The authors first conducted a principal components analysis of each battery. With respect to the memory tests, they found that all the between-task correlations were positive but relatively low; the first factor accounted for only 27% of the variance. This is lower than for the other two batteries, that is, the intelligence tests battery and the reaction times battery, in which the first factor accounted for 37% and 71%, respectively. A factor analysis including all the tests used in the battery also showed a greater heterogeneity among the memory tests, all of which did not load on the same factor. The authors then computed correlations between the factor scores obtained for the first factor of each battery; coefficients were significant, with values around .40. Finally, using partial correlations and multiple regression analyses, the authors concluded that STM plays the role of a mediating variable between processing speed and intelligence.

Within the neo-piagetian context, Portath (1992) and Crammond (1992), whose work was mentioned earlier, report correlations around .40 between counting span and visual span after controlling for age. Morra (1992; 1994) was interested in showing the existence of an M factor in the sense of Pascual-Leone’s model over several studies. STM tasks such as simple span tasks, and attentional capacity tasks inspired by Pascual-Leone & Case were administered together with other tasks (articulatory speed, g factor tests, spatial and verbal ones). In a principal components analysis, M tests were indeed found to load on a same factor; in contrast, STM tests did not load on a single factor, but were grouped according to their content (verbal or spatial).

Finally, in a five-year longitudinal study conducted with children originally aged from 5 to 10 years of age, we used four WM tests each year. Three non-verbal tests adapted from Pascaul-Leone and/or Case were used each year; the fourth changed almost every year, and verbal WM tests were also used (Counting Span, Listening Span and Reading Span). Confirmatory factorial analyses showed that a model postulating a single factor each year was satisfactory; in addition, this factor seemed stable from one year to the next (de Ribau-pierre & Bailleux, in press). Although age explained a large part of the common variance, it was not sufficient to account for this single factor. Therefore, it could be concluded that these different tests indeed tap common processes. However, it should also be emphasized that there were important situational changes; for instance, changes in the response mode introduced an important change in the scores obtained (de Ribau-pierre & Bailleux, 1994).
this results in probably premature conclusions about the generality of some phenomena and some unexplained phenomena. Consequently, the concept of WM remains controversial, although it has certainly been useful to account for a certain number of effects, as Baddeley (1992b) rightly underscores.

The question of whether all individuals use the same processes in a same task has seldom been explored. The study of DeLea Sala et al., reported above, seems the first step in this direction; it led indeed to a slight modification of the general model, even though it was relatively restricted in scope since it addressed only the phonological loop. The model that Reuchlin (1978) proposed of vicarious, or optional, processes could prove useful in this area, too. It seems that different individuals may prefer using different types of processes in the same situation, provided all these processes present some efficiency. Ohlmann, for instance, demonstrated the existence of such vicarizations in the perception of verticality (e.g., Ohlmann, 1990, 1993; see also de Ribaupierre, 1989). There is no such empirical evidence, or very little, in the field of working memory, but some new studies suggest this possibility. For instance, two cases of marked developmental dyslexia were reported (cases RE and JM, cited in Hulme & Mackenize, 1993), who presented a serious deficit in STM and had nevertheless excellent cognitive aptitudes including reading comprehension. This demonstrates that the strategies were able to use compensatory, alternative strategies to the transition of compensatory strategy to vicarizations is relatively easy, at least in theory. The question is whether such alternative strategies do also exist in “normal” individuals. A modelisation of WM in terms of vicarious processes requires to adopt different experimental paradigms. First of all, the task should not induce the presupposition or the transition of use of one type of process (Ohlmann, 1993); in most WM studies, the tasks indeed compel the use of a given processing mode, usually verbal. If the tasks were more open to different modes of processing, it is likely that certain subjects would prefer to encode and maintain the material by means of the PL, whereas others might prefer to use the VSSP. Several types of tasks should also be used with the same subjects to determine if there are different patterns for different types of subjects. Incidentally, the distinction between PL and VSSP is very similar to the long-standing psychometric distinction established between a verbal and a spatial factor. It is also relatively close to the distinction which was introduced between a propositional and an analogical modes of representation (e.g., Kosslyn, 1980). This last distinction proved useful to analyze not only between-task differences, but also individual differences and possible interactions between types of situations and types of subjects (e.g., Laurent, 1990; de Ribaupierre, Rieben & Laurent, 1991; Rieben, de Ribaupierre & Laurent, 1990). This type of approach requires to administer tasks that can be processed in several ways (this possibility being the object of preliminary theoretical task analyses), and/or several types of task. Roulin proposed recently tasks that seem quite relevant for this type of research. For instance, in a double span task (Loisy & Roulin, 1992), subjects have to encode words in particular positions, and recall either the words, the positions, or both. In another task (Roulin & Monnier, 1992; Monnier, 1994), subjects have to add digits presented in different positions, and have therefore to associate the result of the operation to a particular position. These two tasks apparently call for the three components of WM defined by Baddeley, and one can think that they should offer evidence individual differences of a more qualitative nature. The Mr Peanut task used in longitudinal study (e.g., de Ribaupierre & Baileux, 1994; see also Case, 1985) also seems to allow several, non exclusive modes of encoding. Subjects are presented a clown figure comprising a certain number of colored spots that they have to memorize, in order to replace them on a blank outline. It is a verbal-non verbal task; the positions can, however, be verbalized since they correspond to different body parts. Consequently, certain subjects might prefer using verbal encoding and rehearsal whereas others may rely on a predominantly visuo-spatial mode of encoding. The purpose of experiments currently in progress in our laboratory is to study the different strategies applied by subjects in this task, using concurrent verbal and spatial tasks as well as a number of other verbal and spatial tests in order to differentiate types of subjects. Preliminary results (Bailieux, Lecerf, & de Ribaupierre, 1994) indicate that adults resort primarily to verbal encoding in this task whereas children would rely mainly on a visuo-spatial mode of encoding. However, there seem to be important individual differences.

To conclude, we wish to emphasize the fact that Pascual-Leone’s model, mentioned several times in this paper, also supports a hypothesis of qualitative individual differences regarding the functioning of WM, although there has not been, to our knowledge, any empirical study in this direction. Restricting the term of WM to what Pascual-Leone calls the mental attentional field and which we compared above to the central executive in Baddeley’s model, one might think that subjects could reach a similar performance by different means. They could succeed in the coordination of two simple tasks (task involving the CE according to Baddeley) either because they have a relatively large M capacity or because they have available particularly efficient executive schemes together with a strong interruption operator which would prevent them from being disturbed by reciprocal interference between the two tasks. Conversely, subjects could experience difficulties in this paradigm because any of these processes functions less efficiently. It is in these terms that Pascual-Leone analyzed differences between field dependent and field independent subjects (Pascual-Leone, 1989; de Ribaupierre, 1983). To test this hypothesis further, it would be necessary to administer tasks involving the different processes, such as not only the coordination paradigm, but also other M tasks and interference paradigms.

References


Address of correspondence:
Anik de Ribes-Tierrier, Faculté de Psychologie et des Sciences de l’Education, Université de Genève, 9, rue de Drize, CH-1227 Carouge, e-mail: derib@unige.ch