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The Development of Working Memory: Exploring the Complementarity of Two Models

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ABSTRACT

The aim of the paper was to further explore the complementarity of the working memory models postulated by Pascual-Leone and Baddeley. Five-, six-, eight- and nine-year-old children were assessed on two working memory tasks, which have frequently been used within the respective streams of research: the Mr. Peanut task and the Corsi blocks task. Results indicated a developmental increase in spatial short-term memory for both tasks. Concurrent spatial suppression reduced performance on the two tasks in all four age groups. By contrast, articulatory suppression only interfered with recall on the Mr. Peanut task, and only in the older children. The two models were shown to make their own specific contribution to the interpretation of the data, attesting to their complementarity. Pascual-Leone's theory offered a clear explanation of the results concerning the central aspects of working memory, i.e. the stepwise age-related increase in performance, whereas Baddeley's model provided a convincing account of the findings regarding the peripheral phonological and visuo-spatial components, i.e. the effects of articulatory and spatial suppression.

Key Words: short-term memory; spatial memory; information processing capacity; memory development; working memory models; rehearsal strategies; cognitive development.

INTRODUCTION

Working memory refers to a system for temporary storage and manipulation of information during the performance of a wide range of cognitive tasks, such as comprehension, learning and reasoning. With regard to the development of working memory, two lines of research can be distinguished: the neo-Piagetian perspective (e.g., Case, 1985; Pascual-Leone, 1970, 1987) and the approach which stems from Baddeley and Hitch's model (Baddeley, 1986, 1990; Baddeley & Hitch, 1974). Despite their common field of study, the two streams of research developed rather independently.

The neo-Piagetian perspective accounts for cognitive development in terms of information processing. A fundamental claim of this approach is that limits in working memory capacity impose constraints on cognitive processes, and vary with age. Neo-Piagetian theorists consider the development of working memory to be a causal factor of cognitive growth across domains. As a result, neo-Piagetian research largely concentrated on developing theories of information processing capacity, more specifically to explain and predict its development. Although a number of different neo-Piagetian models of working memory have been formulated, the present study shall only focus on Pascual-Leone's theory of constructive operators.

Baddeley and Hitch's working memory model was not explicitly devised with a view to explaining developmental data, but to provide an adequate account of short-term memory phenomena in adults. It has recently been applied to the development of short-term memory in children (e.g., Hitch, Halliday, Dodd, & Littler, 1989a).

PASCUAL-LEONE'S MODEL

Pascual-Leone (1970; Pascual-Leone & Baillargeon, 1994; Pascual-Leone & Morra, 1991) proposed a mathematical model to account for the development of attentional capacity. His multidimensional model includes two levels of psychological constructs: schemes, derived from Piaget's theory, and silent or hidden hardware operators. Schemes constitute the basic units of cognition; they are information-bearing, situation-specific constructs that generate performance. Schemes differ in content and modality, and can be classified as figurative or operative. The former represent cognitive states, whereas the latter stand for transformations from one mental state to another. Executive schemes, which are responsible for the control of performance, are a subdivision of the operative schemes. Hardware operators are non-

informational, content-free processing resources. These innate processing resources represent the functional modules of the brain's hardware utilities, such as mental attention and structural learning, that are applicable across situations. They provide activation energy for the schemes, and are called 'silent' or 'hidden' because they only have an indirect manifestation on performance through the effects they induce on schemes. A number of hardware operators have been postulated, such as a Content-learning and a Logical-structural learning operator, a Field effects operator which minimises the complexity of performance, an Interrupt-operator which inhibits activation of task-irrelevant schemes, a Mental energy operator which boosts the activation of task-relevant schemes that are not sufficiently facilitated by other hardware operators, etc. According to the theory of constructive operators, cognitive performance is co-determined by the interaction of schemes and hardware operators. When an input is given, a number of schemes are activated; together they constitute the "field of mental attention" or working memory. The selection and activation of these schemes depends on three mechanisms: the M-operator, the I-operator and the executive schemes.

Of the various hardware operators, Pascual-Leone only made precise developmental predictions with regard to the M-operator. M-capacity or M-power is defined as the maximum number of discrete chunks of information or independent schemes that can be simultaneously activated within a single mental operation. The size of the M-operator is limited and, when measured behaviourally, it increments in integer steps corresponding to successive Piagetian stages as a function of chronological age. Empirical evidence validates the assumption that M-capacity increases by one informational unit every second year, from 1 at the age of 3 to the adult capacity of 7 at the age of 15 (e.g., Johnson, Fabian, & Pascual-Leone, 1989; Morra, Moizo, & Scopesi, 1988). Maturational growth in M-capacity accounts for developmental changes in cognitive performance, such as language (Johnson et al., 1989), motor performance (Todor, 1979) and moral judgement (Stewart & Pascual-Leone, 1992).

BADDELEY AND HITCH'S MODEL

Baddeley and Hitch's working memory model consists of a central executive assisted by two slave systems, the phonological loop and the visuo-spatial sketch pad. The central executive is an attentional control system with limited resources. It is responsible for the transmission of information from short-term memory to long-term memory, strategy selection, and co-ordinating the activities of the subsidiary slaves. The phonological loop is involved in

the temporary storage and processing of verbal material. The visuo-spatial sketch pad is responsible for the temporary retention and manipulation of visuo-spatial information, and has been found to involve resources distinct from the phonological loop (e.g., Brooks, 1967; Logie, Zucco, & Baddeley, 1990).

Research efforts in the past have largely focused on the phonological loop. This component has been shown to comprise two subsystems: a passive phonological store which is accessed directly by auditory presented material and can hold a limited amount of speech-based material, and an active articulatory loop mechanism that refreshes memory traces, which rapidly decay in the phonological store (Schweikert & Boruff, 1986), by the process of subvocal rehearsal. The articulatory control process can also translate visually presented information into a phonological code.

Guided by the knowledge from studies on adult working memory, researchers within the area of developmental psychology have attempted to determine whether Baddeley's concept can be generalised to children. Due to its complexity and lack of specificity developmental psychologists have paid little attention to the central executive. Most of the research activity has been devoted to the development of the currently better understood slaves, the phonological loop in particular.

The working memory framework can provide a persuasive account of the development of rehearsal strategies. The use of subvocal rehearsal has been shown to develop earlier for spoken words than for pictures (Halliday, Hitch, Lennon, & Pettipher, 1990; Hitch et al., 1989a; Hitch, Halliday, & Littler, 1989b; Hitch, Halliday, Schaafstal, & Schraagen, 1988; Hitch, Woodin, & Baker, 1989c; Hulme, Thomson, Muir, & Lawrence, 1984; Hulme & Tordoff, 1989; Johnston, Johnson, & Gray, 1987). This can be interpreted in terms of an optional recoding process that visual inputs have to undergo in order to gain access to the phonological store, whereas spoken materials have automatic access. Since their use of the articulatory rehearsal process is not yet fully developed, young children do not recode visually presented material into a verbal form, whereas older children, like adults, do. Instead they rely on visual codes to retain pictorial material. From about the age of 8 years, children can use both visual and verbal codes but tend to rely on the latter, regardless of the modality in which materials are presented. Thus, the developmental pattern is one in which visual coding is complemented rather than replaced by phonological coding.

Little is yet known concerning the development of the visuo-spatial sketch pad. Hitch et al. (1989a) employed the Corsi blocks task (Milner, 1971) to determine the developmental

trend of visuo-spatial short-term memory. Visuo-spatial memory span was found to improve gradually between the ages of 4 and 11. In addition, Wilson, Scott, and Power (1987) demonstrated that pattern span increases rapidly between the ages of 5 and 11, by which time it is at the adult level. Furthermore, Walker, Hitch, Doyle, and Porter (1994) showed a developmental enhancement in memory for spatial location on a probed location memory task.

COMPARISON OF TWO WORKING MEMORY MODELS

In the recent literature several authors have raised the idea that the theories posited by Pascual-Leone and Baddeley may in fact be complementary (e.g., Hitch & de Ribaupierre, 1994; de Ribaupierre, 1995; de Ribaupierre and Bailleux, 1994, 1995). They discussed a number of theoretical points of convergence and divergence between the two conceptual frameworks, some of which will be briefly summarised (for a detailed review, see de Ribaupierre and Bailleux, 1994). The present paper, however, is essentially of an empirical nature, rather than a theoretical one.

At face value the models proposed by Pascual-Leone and Baddeley seem very different and rather incompatible. First of all, the core of neo-Piagetian research is to explore whether the developmental increase in working memory can account for cognitive development at large. Baddeley's working memory model, however, was created to provide an account of the functioning of working memory in adults. Second, Pascual-Leone's theory provides an empirically validated quantitative prediction of age-related increase in working memory capacity. Developmental studies based on Baddeley's model, however, have made no attempt to formulate precise developmental predictions; hence, the contribution of research that has focused on developmental differences in working memory within this framework has remained purely descriptive. Third, Baddeley regards working memory as a system with its own specific processes, whereas Pascual-Leone considers working memory to be an activated subset of long-term memory. Fourth, research efforts within Pascual-Leone's perspective have almost been entirely devoted to the central attentional component (M-operator) of working memory, while Baddeley and Hitch focused primarily on the peripheral phonological and visuo-spatial components. Fifth, research inspired by Pascual-Leone's model tends to use a single task or a battery of tasks; studies within the Baddeley tradition, however, frequently use a dual task paradigm.

Regardless of their differences, the theories conceptualised by Pascual-Leone and Baddeley are much closer than it first appears. As noted above, the two models assume working memory to be a non-unitary system. In addition, they can both account for the age-related increase in the size of working memory during childhood (Baddeley, 1986; Pascual-Leone, 1970). According to Pascual-Leone cognitive development is determined by a stepwise increase in M-capacity every odd year from the age of 3 to late adolescence. Baddeley does not address the role of maturation at length, but accounts for the development of verbal span in terms of an increase in articulatory speed.

Besides their similarities, there are other reasons for bringing these two models together. Both from an empirical and an epistemological perspective, it makes sense to compare two approaches to working memory which developed within very different perspectives and have evolved rather separately. Drawing links between two streams of research promotes the exchange of ideas, methods, data and interpretations of empirical results. In addition, it would make for fruitful theoretical development.

The possibility of a rapprochement between the theoretical constructs proposed by Pascual-Leone and Baddeley first dawned on de Ribaupierre and Bailleux (1994) when they conducted a longitudinal study which was initially designed to examine some of Pascual-Leone's postulates regarding the existence of neo-Piagetian stages in the development of attentional capacity, using a number of neo-Piagetian tasks. In the course of their study they realised that some of their results could just as well be interpreted within Baddeley's model.

They examined the attentional capacity of four cohorts of children, aged 5, 6, 8 and 10 years with a short-term spatial memory task adapted from Case (1985), Mr. Peanut. In this task a clown figure (see Fig. 1) is presented with a number of coloured dots on different parts of its body. It is then removed and replaced with an identical blank clown figure. Subjects have to place coloured chips on the parts that were painted in the previous picture. Two versions were used: a uni-coloured task (Peanut-P), in which subjects had to recall the positions of the dots, and a multicoloured task (Peanut-C), in which subjects had to recall both the positions and the colours of the dots.

Insert Fig. 1 about here

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de Ribaupierre and Bailleux found their data to be compatible with both working memory models. In particular they argued that Pascual-Leone's theory could provide a more

solid account of one set of empirical findings, whereas Baddeley's model could offer a sounder explanation for another set of results. For instance, the finding that performance on Peanut-P increased steadily with complexity, while performance on Peanut-C tended to stabilise beyond a certain level of complexity, could be more easily interpreted within Pascual-Leone's model. Baddeley's model, however, could better account for the drop in performance in the fourth year due to computerisation of the task; responding with a computer mouse relies on the same subsystem as the Mr. Peanut task, i.e. the visuo-spatial sketch pad, leaving less processing resources for recall. Due to its assumption of independent subsystems for verbal and visuo-spatial material, Baddeley's model was also more apt to interpret the finding that employment of the mouse device interfered more with the recall of positions than colours (for a detailed description of the results and a more elaborate discussion of the interpretation of the data within the two working memory models, see de Ribaupierre and Bailleux, 1994). This led the authors to conclude that the two models are complementary rather than contradictory.

EMPIRICAL DEMONSTRATION OF COMPLEMENTARITY

The aim of this paper was to further explore the complementarity of the models postulated by Pascual-Leone and Baddeley. More specifically, it built upon and extended the work of de Ribaupierre and Bailleux (1994) in two ways. First, de Ribaupierre and Bailleux came to the conclusion of complementarity post hoc, in light of their data. Therefore, their study served more as an illustration of complementarity than as an empirical demonstration. The present study, however, was designed with the objective to demonstrate the complementarity of the two working memory models with empirical data. As briefly mentioned in the Introduction section, the complementarity of the two working memory concepts is both a theoretical and an empirical matter. The epistemological issue of complementarity rests on a theoretical analysis of the two models. The empirical nature of the complementarity argument, however, can be demonstrated experimentally, in the sense that it can be shown how each model makes its own contribution to the interpretation of the data. The present study was essentially concerned with this empirical aspect of complementarity. Second, de Ribaupierre and Bailleux claimed that Baddeley's model offered a plausible alternative to Pascual-Leone's theory for interpreting their results obtained within a neo-Piagetian framework, using a well-known neo-Piagetian task. The present work investigated

whether Pascual-Leone's theory in turn complements Baddeley's model. In other words, does the complementarity of the two models hold both ways?

For these purposes the development of working memory was assessed in four groups of children, aged 5, 6, 8 and 9 years, using two working memory tasks: the Mr. Peanut task and the Corsi blocks task. Both tasks have an established reputation within their respective domains. The Mr. Peanut task was constructed by DeAvila (1974) and Diaz (1974) as a measure of M-capacity, and modified versions have frequently been employed within developmental psychology (e.g., Case, 1985). The Corsi blocks task was designed as a neuropsychological test for assessing spatial short-term memory (Milner, 1971), and has been associated with the visuo-spatial sketch pad in Baddeley's model (Hanley, Young, & Pearson, 1991). It has proven to be a fruitful technique in research on spatial ability across a wide range of domains, such as cognitive psychology (e.g., Smyth & Scholey, 1992, 1994), developmental psychology (e.g., Hitch et al., 1989a) and neuropsychology (e.g., De Renzi & Nichelli, 1975).

To demonstrate that the models postulated by Pascual-Leone and Baddeley can indeed complement each other, it should be shown that each model makes its own contribution to the interpretation of the empirical results. The Mr. Peanut task and the Corsi blocks task were carefully selected with the intention of testing a number of hypotheses aimed at assessing the specific contribution of the two models. Also, in order to keep things relatively simple, the scope of the present work was limited to working memory tasks with a strong spatial component.

To explore the mutual complementarity of the two approaches, hypotheses were tested about effects typical of each of the models[1]. Typical of Pascual-Leone's model is the assumption of a stepwise increase in the number of units that can be processed simultaneously in accordance with Piagetian stages of development (Pascual-Leone, 1970). Hence, it was hypothesised that performance on both tasks will reveal an age-related increment of one unit every two years. Typical of developmental studies generated from Baddeley's perspective is the hypothesis of a progressive complementation of visual coding by phonological coding with age (Halliday et al., 1990; Hitch et al., 1988, 1989a,c). To test this hypothesis both tasks were administered with concurrent verbal suppression. Unlike the Corsi blocks task, the Mr. Peanut task is prone to verbal encoding. The body parts of the clown figure can be labelled. If inner speech does indeed play a role in the Mr. Peanut task, articulatory suppression will be expected to exert different effects in the younger (5- and 6-year-olds) than the older (8- and 9-

year-olds) children. Concurrent verbal suppression is not expected to interfere with performance of the younger children as they do not verbally recode visual information. The older children, however, may tend to rely on phonological codes. Hence, their performance is expected to suffer under articulatory suppression. The Corsi blocks task has been shown to be a purely spatial task (e.g., Smyth, Pearson, & Pendleton, 1988). Consequently, no effect of verbal suppression is expected. However, both tasks are expected to be susceptible to spatial interference in all four age groups. The effects of verbal and spatial suppression can be best accommodated by Baddeley's model, for the employment of a dual task paradigm to identify the contribution of the different components of working memory is characteristic of studies within this working memory framework.

METHOD

Subjects

A total of sixty children participated in the study: fifteen 5-year-olds (mean age 5 years; range 4 years 11 months to 5 years 1 month), fifteen 6-year-olds (mean age 6 years; range 5 years 11 months to 6 years 1 month), fifteen 8-year-olds (mean age 8 years; range 7 years 11 months to 8 years 1 month), and fifteen 9-year-olds (mean age 9 years; range 8 years 11 months to 9 years 1 month). A strict selection criterion was used: On the day of the experiment children were within a month of their birthday. The choice of these four age groups allowed us to test Pascual-Leone's assumption that the development of M is stepwise, by contrasting contiguous age groups supposed to belong to the same stage (5- and 6-year-olds) with contiguous age groups supposed to belong to a different stage (8- and 9-year-olds). In addition, the selection of these age groups reflected the objective to test the hypothesis of a progressive complementation of visual coding by phonological coding with age. The children were recruited from four primary schools in Ghent, Belgium.

Design

The experiment was a 4 (age: 5-, 6-, 8- and 9-year-olds) x 2 (task: Mr. Peanut task, Corsi blocks task) x 3 (suppression: control, verbal suppression, spatial suppression) factorial design.

Tasks

To parallel the spatial nature of the Corsi blocks task, the original uni-coloured variant of the Mr. Peanut task was employed. In this task a two-dimensional outline of a clown figure is presented to which a number of purple dots are attached. Exposure time varies with the number of presented dots: one dot per second. The subject is then given a blank outline of the clown figure and is instructed to point to those parts of its body that previously had a dot on them. In the construction of this task a number of specific conditions were met. Symmetrical locations (e.g., the two eyes) were precluded, and obvious patterns and perceptual configurations were avoided as much as possible to prevent subjects from creating spatial patterns and chunking.

The apparatus for the Corsi blocks task consists of a set of nine black blocks (4 x 4 x 4 cm) arrayed in a quasi-random pattern on a black wooden board (26 x 32 cm). The experimenter taps a particular sequence of blocks at a rate of one per second; the subject is required to tap out the same pattern immediately afterwards. No block is presented twice on any trial. To facilitate presentation and scoring, the sides of the blocks facing the experimenter are numbered; these numbers are not visible to the subject.

Both tasks are clearly spatial. Nevertheless, there are a number of procedural differences typical of the two tasks which were retained in this experiment to ensure that results cannot be ascribed to a parallelism between the tasks. First, in the Corsi blocks task the targets are presented sequentially, by contrast with the Mr. Peanut task which employs a simultaneous presentation procedure. Second, the Corsi blocks task requires serial recall, whereas in the Mr. Peanut task free recall is requested.

In the articulatory suppression task, subjects were instructed to continuously repeat the word "the" during presentation (Levy, 1971). The spatial suppression task entailed the continuous sequential tapping task (Farmer, Berman, & Fletcher, 1986). Subjects were required to repeatedly tap four metal plates positioned in a square pattern arrangement, working in a clockwise direction.

Procedure

The subjects were tested individually in a quiet room. To avoid possible problems of fatigue the experiment was conducted in two sessions of approximately 20 min. Half the subjects performed the Mr. Peanut task in the first session and the Corsi blocks task in the

second, for the other half the order was reversed. The order in which the suppression conditions were administered was fully counterbalanced across subjects.

At the beginning of each session the memory task was explained and children were given time to practice to ensure they understood the nature of the task. Prior to each experimental condition, the suppression task was demonstrated and children were given additional practice. To safeguard against possible general attentional effects of the suppression tasks, training was continued until these became familiar to them, although experimental studies have shown that such demand characteristics can be excluded (e.g., Halliday et al. 1990).

For both tasks, in the test proper three trials were given at each sequence, beginning with trials consisting of one item. If two out of three sequences were repeated correctly, the sequence length was increased by one. When the subject failed on two or more trials of a given length testing was discontinued. Each correct trial counted as $^1/_3$; the total number of thirds was added up to provide a span score (Smyth & Scholey, 1992). This measure has been shown to be more sensitive than the simpler alternative of taking span as the longest sequence length for which two out of three sequences are correctly recalled.

RESULTS

Due to extremely deviant performance (i.e., observations outside the range of +/- 2 standard deviations around the group mean), data of two children were discarded. In accordance with suggestions formulated by McCall and Appelbaum (1973) for the analysis of repeated measures designs, a multivariate analysis was performed with contrasts in the dependent variables, the span scores in each of the task x suppression cells. The between-subjects effect of age, and the within-subjects effects of task and suppression were analysed.

The analysis revealed main effects of age, $F(3, 54) = 83.91$, $p < .001$, task, $F(1, 54) = 44.20$, $p < .001$, and suppression, $F(2, 53) = 78.48$ $p < .001$. There was also an interaction between age and task, $F(3, 54) = 4.52$, $p = .007$, and a significant task x suppression interaction, $F(2, 53) = 4.10$, $p = .022$. The other interactions between the independent variables were not statistically reliable.

As noted above, the present study focused on a number of hypotheses with respect to demonstrating the specific contribution of each working memory model to the interpretation of the results. To this end, the data were subjected to planned comparisons. Results of these

analyses are reported per task. One important yet remarkable finding should be retained from the global analysis though: Performance on the Corsi blocks task ($M = 3.33$, $SD = 0.88$) was consistently higher than on the Mr. Peanut task ($M = 2.83$, $SD = 1.05$), both across age groups and suppression conditions.

Mr. Peanut Task

Analysis of performance in the control condition yielded a stepwise increase congruent with the neo-Piagetian postulate of developmental stages lasting for two years, $F(3, 54) = 53.81$, $p < .001$. Average span scores were 2.16 ($SD = 0.36$) for the 5-year-olds, 2.38 ($SD = 0.47$) for the 6-year-olds, 3.78 ($SD = 0.79$) for the 8-year-olds, and 4.56 ($SD = 0.56$) for the 9-year-olds. The difference in performance between the 5- and the 6-year-olds was not significant, $F(1, 54) = 1.07$, $p = .305$, whereas the 9-year-olds scored significantly better than the 8-year-olds, $F(1, 54) = 12.49$, $p < .001$. The difference in recall between the 6- and the 8-year-olds was statistically reliable too, $F(1, 54) = 42.64$, $p < .001$. As is shown in Fig. 2, both suppression conditions revealed a similar developmental trend ($F(3, 54) = 22.52$, $p < .001$ for articulatory suppression, and $F(3, 54) = 27.10$, $p < .001$ for spatial suppression), with the exception that the 8- and 9-year-olds did not differ from one another in the spatial suppression condition, $F(1, 54) = 1.57$, $p = .216$.

Insert Fig. 2 about here

Analyses of the suppression conditions showed the following pattern of results. Spatial suppression impaired performance both overall, $F(1, 54) = 65.37$, $p < .001$, and across the different age groups ($.001 < p < .01$). Moreover, the 9-year-olds were particularly disrupted by the spatial suppression task, relative to the 5- and the 6-year-olds ($.01 < p < .05$), but not in relation to the 8-year-olds ($p > .05$). In spite of an overall effect of articulatory suppression, $F(1, 54) = 19.32$, $p < .001$, planned contrasts revealed differential effects of articulatory suppression according to age group. In line with Baddeley's hypothesis of a progressive dependence on phonological codes with age, articulatory suppression had a clear disruptive effect in the older children (8-year-olds: $F(1, 14) = 12.67$, $p = .003$; 9-year-olds: $F(1, 12) = 4.81$, $p = .048$), but not in the younger ones (5-year-olds: $F < 1$; 6-year-olds: $F(1, 14) = 2.76$, $p = 0.119$). Both the absolute and the relative amount of interference were greater for the older

children than for the younger. In terms of percentage, the mean decline in performance in the verbal suppression condition compared to the control condition was 1.42% for the 5-year-olds, 8.52% for the 6-year-olds, 16.59% for the 8-year-olds, and 10.78% for the 9-year-olds. Moreover, the spatial suppression task was more disruptive than the verbal suppression task in both the 5-year-olds, $F(1, 14) = 13.91$, $p = .002$, and the 9-year-olds, $F(1, 12) = 6.29$, $p = .027$, but not in the 6-year-olds, $F(1, 14) = 1.47$, $p = 0.245$, and the 8-year-olds, $F < 1$.

Corsi Blocks Task

Conformable to the analysis of the Mr. Peanut task a developmental effect was observed in the control condition of the Corsi blocks task, $F(3, 54) = 26.16$, $p < .001$. Average level of performance was 2.84 ($SD = 0.48$) for the 5-year-olds, 3.29 ($SD = 0.54$) for the 6-year-olds, 4.33 ($SD = 0.56$) for the 8-year-olds, and 4.31 ($SD = 0.56$) for the 9-year-olds. Again spatial span did not differ between the 5- and the 6-year-olds, $F(1, 54) = 3.88$, $p = .093$. By contrast with performance on the Mr. Peanut task, recall scores of the 8- and 9-year-olds were not different from one another either, $F < 1$. However, the 8-year-olds recalled significantly more blocks than the 6-year-olds, $F(1, 54) = 26.44$, $p < .001$. Fig. 3 shows similar developmental curves for the two suppression conditions, $F(3, 54) = 24.85$, $p < .001$ for articulatory suppression, and $F(3, 54) = 29.11$, $p < .001$ for spatial suppression.

Insert Fig. 3 about here

Spatial suppression had a detrimental effect on memory span, $F(1, 54) = 89.80$, $p < .001$. Performance did not suffer, however, when subjects were required to suppress articulation, $F(1, 54) = 1.43$, $p = .237$. These results were true for each of the four age groups.

DISCUSSION

The present study further explored the complementarity of the working memory constructs proposed by Pascual-Leone and Baddeley. The research was a follow up of the work by de Ribaupierre and Bailleux (1994) regarding two issues. First, unlike the de Ribaupierre and Bailleux study, the present work was designed with a view to provide an empirical demonstration of the complementarity argument. Second, de Ribaupierre and Bailleux showed that Baddeley's model was an alternative to Pascual-Leone's theory for

interpreting some of their data obtained within a neo-Piagetian research paradigm. This paper explored whether Pascual-Leone's model could also complement Baddeley's theory.

To show that the streams of research can indeed complement each other, hypotheses typical of either perspective were tested to assess their specific contribution to the interpretation of the data. To this end the development of working memory was assessed on two tasks, which have frequently been used within the respective theoretical frameworks: the Mr. Peanut task and the Corsi blocks task.

The finding that performance was consistently better on the Corsi blocks task than on the Mr. Peanut task was rather surprising. Surely a free recall procedure would be expected to produce higher scores than a serial recall task. This pattern of results could be attributed to the different number of possible spatial positions in the two tasks. The dots in the Mr. Peanut task can appear in fourteen different places, allowing somewhat more variation than the nine locations of the Corsi blocks task. It is certainly easier to discriminate a set of spatial targets among a smaller number of possibilities. Alternatively, the unexpected result could be due to the manner in which the stimuli were presented. In the Mr. Peanut task children may be overwhelmed by the amount of information presented at the same time. They cannot rely on external aid to focus their attention. As such, the information load they have to deal with simultaneously may be a source of distraction. In the Corsi blocks task, however, a sequence of movements is constructed step by step. Children are guided to concentrate on one block at a time. Yet another explanation for this unexpected finding could be the differences in the material employed in the two tasks. Unlike the nine identical targets of the Corsi blocks task, the different body parts of the clown figure provide a semantic code. Consequently, they may evoke all sorts of associations which have to be inhibited to successfully perform the task. In that respect the Mr. Peanut task is more complex than the Corsi blocks task, attesting to their discrepant recall scores. Further research bearing upon the underlying mechanisms of the two tasks is needed so as to understand the difference between them.

Returning to the main objective of this study, exploring the complementarity of the research paradigms adhered to by Pascual-Leone and Baddeley, the results are fairly straightforward and generally confirm the hypotheses. First, in line with expectations, both tasks yielded a developmental trend in performance. Perhaps due to a lack of research on the development of visuo-spatial short-term memory within Baddeley's model, this working memory framework cannot really go beyond the general claim of a steady increase in spatial memory span with age. Thus far, no underlying rehearsal mechanism has been found in visuo-

spatial working memory (Smyth & Scholey, 1992, 1994), by analogy with the time-based articulatory rehearsal system in verbal short-term memory. Hence, no particular factor can be put forward to account for this developmental change in spatial recall, analogous to the link between speech rate and the development of verbal span. The neo-Piagetian perspective, however, offers a detailed description and prediction of the age-related increase in information processing capacity. Pascual-Leone (1970) asserts that cognitive development is determined by a stepwise increase in M-capacity every odd year. On average, a 3-year-old child has the capacity to process one representational scheme via the M-operator within a given time span. This capacity increases to two schemes at the age of 5, and continues to increase by one unit every second year until a capacity has been reached with which seven units of information can be activated simultaneously at the age of 15. With reference to the age groups of the present study, the 5- and 6-year-olds would be expected to dispose of a capacity to process two units, the 8-year-olds three, and the 9-year-olds four. If the number of correctly recalled dots is taken as a measure of M-capacity[2], performance in the control condition of the Mr. Peanut task revealed an age-related increment at the approximate rate predicted by Pascual-Leone's theory. The number of elements that could be processed simultaneously in the Corsi blocks task, however, was somewhat higher than would be expected on the basis of Pascual-Leone's model. Several studies on the development of spatial memory span have in fact reported similar span scores (Hitch et al., 1989a; Logie & Pearson, 1997; Orsini et al., 1987; Orsini, Schiappa, & Grossi, 1981). Nevertheless, performance was largely consistent with the developmental step curves proposed by Pascual-Leone. First, no difference in spatial span was expected between the 5- and 6-year-olds, two contiguous age groups belonging to a same M-stage. Second, due to their greater M-capacity the 8-year-olds were expected to recall more blocks than the 5- and 6-year-olds. Both predictions were confirmed by the present experiment. Furthermore, Pascual-Leone's model predicts differential span scores for the 8- and the 9-year-olds, two contiguous age groups belonging to a different M-stage. The latter was not supported by the data. Apparently, the extra unit of information available to the 9-year-olds was not sufficient to improve the number of blocks recalled.

Nonetheless, the results of the older children on both the Mr. Peanut task and the Corsi blocks task are supported by research within the respective working memory frameworks. In comparison to the 8-year-old children, the 9-year-olds attained a higher level of performance on the Mr. Peanut task, but not on the Corsi blocks task. Nine-year-olds can systematically retain one more dot on the Mr. Peanut task as opposed to 8-year-olds, in accordance with

Pascual-Leone's quantitative prediction about the development of cognitive capacity (de Ribaupierre & Bailleux, 1994; de Ribaupierre, Neirynck, & Spira, 1991). Span scores on the Corsi blocks task, however, increase steadily from approximately 4 in children aged 7 years till an average spatial span of 5 is reached at the age of 11 (Hitch et al., 1989a; Logie & Pearson, 1997; Orsini et al., 1981, 1987). Hence, performance on the Mr. Peanut task appears to develop at a rate that is somewhat different from that found for the Corsi blocks task.

In a recent study on the fractionation of visuo-spatial working memory in children Logie and Pearson (1997) also observed different developmental trends on two spatial memory tasks. Using both recall and recognition procedures, they found that pattern memory developed more rapidly with age than memory for movement sequences. This difference in developmental progression was shown to reflect the involvement of different underlying cognitive mechanisms. Similarly, the retention of object locations (Mr. Peanut task) and the retention of a sequence of movements (Corsi blocks task) may, in part, rely on different cognitive resources, giving rise to differential rates of development. Further research into the forms of spatial encoding used in the two tasks should render this basic conclusion more general. Nevertheless, performance on the Corsi blocks task can by and large be interpreted within the neo-Piagetian framework.

In short, the data are broadly consistent with Pascual-Leone's stepwise improvement in span. A continuous developmental change can, however, not be ruled out. With the exception of the non-differential level of performance observed in the 5- and the 6-year-olds, the remaining comparisons between adjacent age groups do not refute a continuous developmental model. Hence, no firm conclusions can be drawn about continuous and stepwise change on the basis of these empirical data alone. Further research including additional age groups, such as a group of 7-year-old children, should yield a stronger test of these two developmental views.

Second, concurrent verbal suppression caused a substantial impairment in performance of the older children on the Mr. Peanut task, but did not interfere with recall in the younger group. Given their even poorer results under spatial suppression, the absence of a verbal interference effect in the younger children is not due to floor effects. This differential effect of articulatory suppression according to age group raises a problem for Pascual-Leone's theory, because no age-related difference is expected in allocating M-capacity to schemes that represent verbal or spatial information. Baddeley's account of working memory, however, can provide a plausible explanation for this developmental effect. The differential effect of

articulatory suppression in the older versus the younger children is in line with the established developmental trends for verbal recoding of visually presented information (Halliday et al., 1990; Hitch et al., 1988, 1989a,c). Developmental approaches within Baddeley's perspective have shown that younger children retain pictorial material in a visual form, and consequently show no effects of articulatory suppression when presented with visual stimuli. Unlike older children, young children do not yet access the articulatory loop to recode visual information into a verbal form for the purpose of short-term retention. In older children, however, articulatory suppression has been found to disrupt their use of verbal memory codes to retain visual material, resulting in poorer recall with visual presentation. The differential effect of articulatory suppression according to age group in the present study indicates that the older children labelled the body parts of the clown figure, whereas the younger children did not. This developmental manifestation of verbal encoding in a predominantly visuo-spatial task demonstrates that inner speech is indeed more important in older children. However, the 6-year-olds in the present study did not seem to rely entirely on visual storage. The articulatory suppression task produced a slight, albeit non-significant, impairment in performance, indicating that at least some of them may already have acquired subvocal rehearsal.

Third, concurrent spatial suppression impaired performance on both tasks in all four age groups. This effect can quite easily be interpreted within the conceptual framework proposed by Baddeley. Both the primary task (i.e., the Mr. Peanut task and the Corsi blocks task) and the suppression task draw on the limited resources of a common subsystem, the visuo-spatial sketch pad. Consequently, less processing capacity remains for retaining information and span scores drop. The result can also be explained in terms of Pascual-Leone's model, but more globally. The secondary task requires additional activation by M; the combined M-demand of the two tasks exceeds the subject's M-power, and hence reduces recall. Moreover, the spatial suppression task is misleading with respect to the primary task. Monitoring both tasks simultaneously, i.e. selecting the relevant schemes activated by the primary task while inhibiting the irrelevant ones activated by the suppression task, requires the intervention of the Interrupt-operator.

With reference to the Mr. Peanut task, the 9-year-olds were particularly impaired by spatial suppression, relative to the two youngest age groups, and relative to the verbal suppression task. The Mr. Peanut task is essentially a spatial memory task, which calls for a spatial memory strategy. This explains the detrimental effect of spatial interference found in every age group. Due to the task's proneness to labelling, children whose use of subvocal

rehearsal is sufficiently developed may choose to complement this spatial memory strategy with a verbal one, which accounts for the adverse effect of articulatory suppression in the older children. The 8-year-olds made good use of this recently acquired rehearsal strategy, all the more so as the verbal and spatial suppression tasks were equally disruptive in this age group. Although the 9-year-olds also used verbal codes in the Mr. Peanut task, at least some of them seemed to prefer a spatial memory strategy. The majority of developmental studies on verbal recoding of visually presented material used line drawings of common objects as stimuli and employed a verbal recall procedure, both of which induce verbal rehearsal. Although most of these studies contrasted 5- or 6-year-olds with 9- or 10-year-olds, those that did include intermediate age groups have shown that the tendency to recode nameable pictures into a verbal form emerges at the age of about 7 or 8 years (e.g., Henry, 1991; Hulme, Silvester, Smith, & Muir, 1986). This emerging tendency to rely on verbal memory codes was also observed in the present study. In addition, labelling pictorial material at presentation has been found to elicit the use of verbal codes in children as young as 5 years of age (e.g., Hitch, Halliday, Schaafstal, & Heffernan, 1991). However, the use of verbal codes only appears consistently and spontaneously in children older than 8 or 9 years. Due to its spatial nature, both in presentation and recall, verbal recoding makes for a less obvious strategy in the Mr. Peanut task, and hence, may not become manifest until children reach the age of 10 or 11. Further empirical evidence bearing upon this issue is of course required.

Fourth, articulatory suppression did not disrupt recall on the Corsi blocks task in any age group. This finding is consistent with numerous studies on adult subjects (e.g., Smyth et al., 1988). It can be successfully incorporated within Baddeley's theory, with reference to the established dissociation between verbal and visuo-spatial processing (e.g., Brandimonte, Hitch, & Bishop, 1992; Farmer et al., 1986). Articulatory suppression and the Corsi blocks task involve separate cognitive structures: The former relies on the phonological loop, the latter on the visuo-spatial sketch pad. Therefore, the spatial task was not adversely affected by verbal interference. This result can also be explained in terms of Pascual-Leone's model by referring to the distinction between activated schemes according to modality and mode. The available M-capacity is allocated to linguistic schemes involved in the encoding of verbal information (articulatory suppression) on the one hand, and to spatio-temporal schemes which support the spatial encoding of the blocks (Corsi blocks task) on the other.

In short, this study lends sustenance to the complementarity between the theoretical constructs proposed by Pascual-Leone and Baddeley, as illustrated by de Ribaupierre and

Bailleux (1994). Each model was shown to make a specific contribution to the interpretation of the data. Pascual-Leone's model could provide a coherent account of the development of the central component of working memory, i.e. the age-related increment in M-capacity, whereas Baddeley's model could successfully explain the developmental fractionation of the peripheral phonological and visuo-spatial components, i.e. the effects of articulatory and spatial suppression. Moreover, consistent with de Ribaupierre and Bailleux's line of reasoning, the present work demonstrated that Baddeley's theory is complementary to Pascual-Leone's model in that it could offer a specific explanation of the differential effect of articulatory suppression according to age group in the Mr. Peanut task, an instrument often used within neo-Piagetian research. In addition, Pascual-Leone's theory was shown to complement Baddeley's model, in the sense that it could, to a certain extent, give a developmental account of the age-related performance on the Corsi blocks task, frequently employed within Baddeley's working memory framework.

As mentioned above, the complementarity of the two theoretical approaches is both an empirical and a epistemological issue. From the data it can be concluded that the two approaches to working memory are indeed complementary at an empirical level: Pascual-Leone's theory could give a quantitative prediction of the age-related performance, whereas Baddeley's theory could give a more parsimonious account of the interference effects.

Similarly, Logie (1991) addressed the issue of complementarity of Baddeley's working memory model and Kosslyn's model of visual imagery regarding experimental findings on visual short-term retention. In addition, Lautrey and Chartier (1991) showed that the Piagetian perspective and theories of information processing complement each other in light of empirical data on the development of mental imagery. Moreover, comparing theoretical models from an empirical point of view has also been found to be a matter of importance in applied research. For instance, Vaquero, Rojas, and Niaz (1996) investigated whether Pascual-Leone's and Baddeley's conceptualisations of information processing could account for academic performance. Using measures of working memory span, structural mental capacity and logical thinking, they showed that performance in science courses could best be accommodated by a model that posits the processing of a large number of bits of information at the same time (Pascual-Leone), whereas performance in language courses could be better explained by a model that postulates simultaneous storage and processing of information (Baddeley).

From a theoretical perspective, the models converge with respect to the notion of an age-related growth in working memory capacity. They differ, however, in terms of underlying assumptions. According to Pascual-Leone, M-capacity increases according to Piaget's qualitative stages of cognitive development. Baddeley, however, attributes the development of (verbal) working memory to an age-related increase in articulation. Due to the empirical focus of the present work, no definite conclusions can be drawn with respect to the theoretical nature of the complementarity argument. A formal theoretical analysis of the two models is required to establish whether they do in fact complement each other in the epistemological sense of the word, or whether perhaps one theory should rather be subsumed under the other, or alternatively, whether an integrated model encompassing both Pascual-Leone's quantitative prediction of the development of working memory and Baddeley's parsimonious account of selective interference effects is to be preferred. However, this was beyond the scope of the present study.

For now, it can be concluded that both theories work, and, at the very least, constitute alternative theoretical approaches to the development of working memory. Although there is no one-to-one correspondence between the two theoretical constructs, further comparison of the models is warranted to advance their possible integration and, if nothing else, to benefit their theoretical development.

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FOOTNOTES

1. We are indebted to one of the anonymous reviewers for his/her help in developing this extension.

2. Pascual-Leone developed a time-based task analysis to determine the M-demand of neo-Piagetian tasks. However, it was not applied in this study.

FIGURE CAPTIONS

1. The clown figure of the Mr. Peanut task.

2. Mr. Peanut task: mean number of correct items for each age group and suppression condition.

3. Corsi Blocks task: mean number of correct items for each age group and suppression condition.
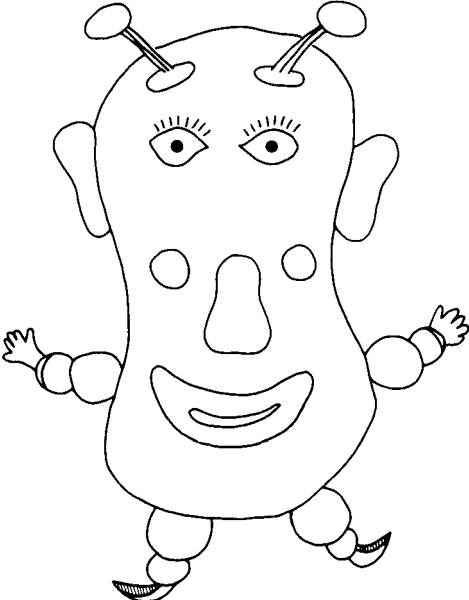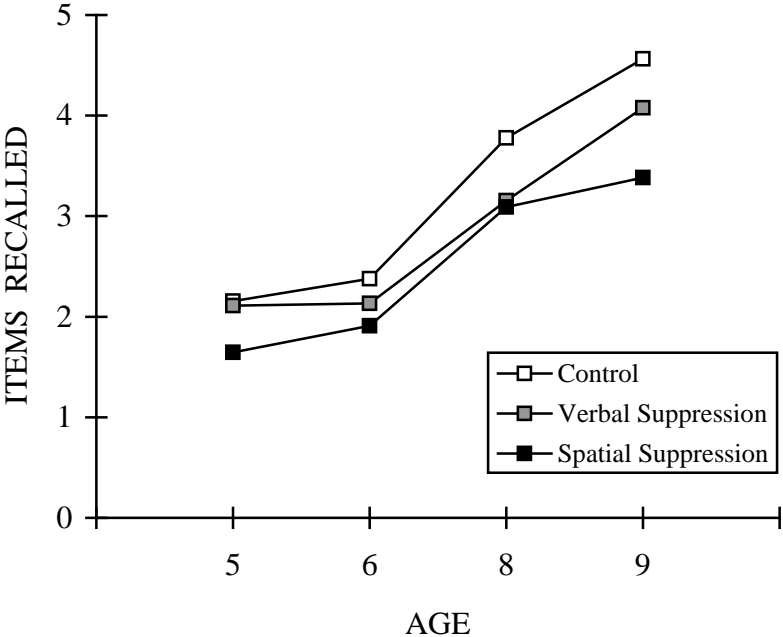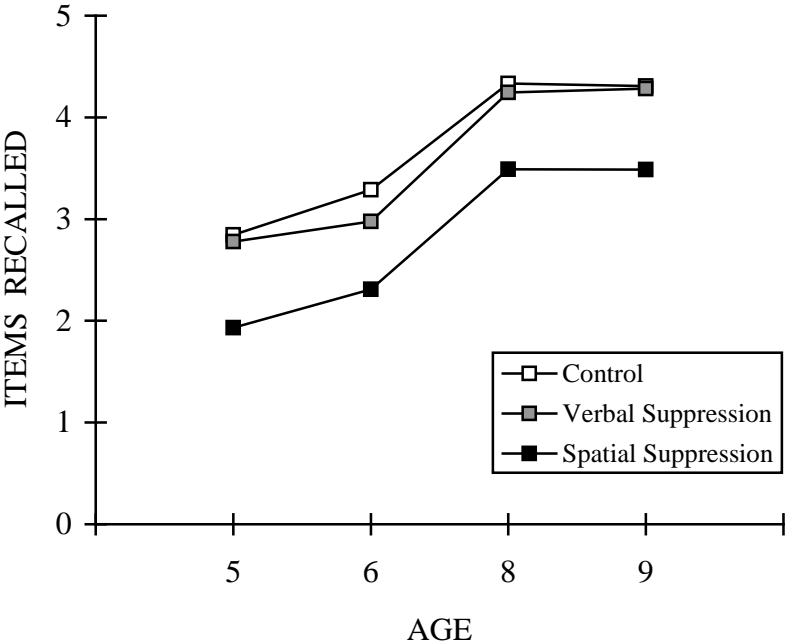
FIG. 1.

FIG. 2.

FIG. 3.